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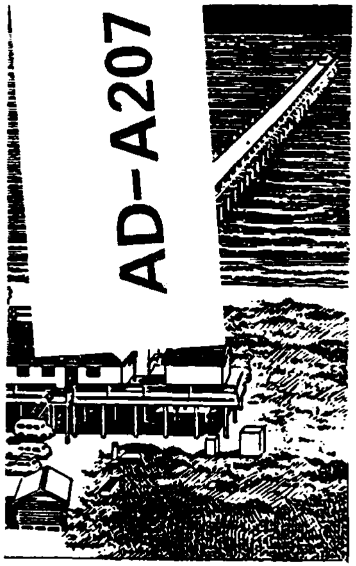

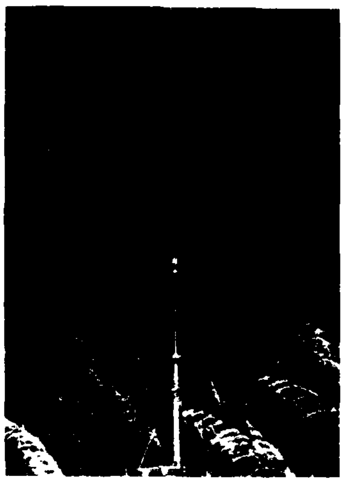

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COASTAL OCEAN DYNAMICS APPLICATIONS RADAR (CODAR) REMOTE SENSING DEMONSTRATION PROGRAM

by

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Coastal Engineering Research Center

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39181-0631

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This report describes the planning, execution, and results of two major field experiments conducted to determine the wave measuring capabilities of the Coastal Ocean Dynamics Applications Radar (CODAR). CODAR is a ground-based, high-frequency radar that uses backscattered energy to determine various ocean surface parameters, such as surface currents and wave height, period, and direction.

Data from CODAR were compared with those from more conventional wave measuring systems, including both directional and nondirectional wave measuring buoys. Agreement between CODAR and buoy data was judged according to predetermined acceptance limits.

The main objective of the program was to establish CODAR as an operational tool for routine use in the collection of coastal wave data. However, results from the comparisons with traditional systems were poor, and CODAR, as tested, cannot be recommended for operational use.

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PREFACE

Results from an extensive program to demonstrate the capabilities of the Coastal Ocean Dynamics Applications Radar (CODAR) are presented in this report. The program was funded by the Operations and Readiness Division, Directorate of Civil Works, US Army Corps of Engineers (USACE). The representatives from Operations and Readiness Division monitoring the program were Mr. Harold Tohlen and Mr. Ted Pelliciotto. Parallel efforts to enhance the CODAR system during the course of the CODAR Remote Sensing Demonstration Program (CRSDP) were funded by the Remote Sensing Research Program, monitored by Messrs. Bob Plott, James Gottesman, and Art Walz, and Dr. Ming Tseng, and formerly Messrs. Ed East and Dave Lichy.

Representatives on the CRSDP Working Group were as follows:

Mr. Jesse A. Pfeiffer, Jr., Directorate of Research and Development, USACE

Mr. John H. Lockhart, Jr., Directorate of Civil Works, USACE

Mr. Dan Muslin, replaced by Messrs. Don Cords and Mike Ellis, US Army Engineer District, Los Angeles

Mr. Herb Maurer, US Army Engineer District, Galveston

Mr. Ronald Vann, US Army Engineer District, Norfolk

Mr. Ken Patterson, US Army Engineer District, Portland

Dr. Edward F. Thompson and Mr. David B. Driver, US Army Engineer Waterways Experiment Station

This report was prepared by Mr. David B. Driver, Physical Oceanographer, Dr. Edward F. Thompson, Hydraulic Engineer, Ms. Linda S. Lillycrop, Hydraulic Engineer, and Mr. Gregory A. Barrick, Contract Student, under direct supervision of Dr. Thompson, former Chief, Coastal Oceanography Branch (COB); and under general supervision of Mr. H. Lee Butler, Chief, Research Division (RD), and Dr. James R. Houston, Chief, Coastal Engineering Research Center (CERC). Dr. Charles L. Vincent, CERC, and Dr. Jon M. Hubertz, Mr. Steven C. Cash, Mses. Willie Ann Brown, Beverly D. Green, and Odia R. Winston, all of COB, provided valuable contributions to various phases of the program. The authors wish to acknowledge the assistance of Ms. Victoria L. Edwards, COB, for preparing the final draft, and Ms. Shirley A. J. Hanshaw, Information Technology Laboratory, WES, for editing this report.

The staff of the CERC Field Research Facility (FRF), located at Duck, North Carolina, under the supervision of Mr. William A. Birkemeier, provided

extensive and essential support throughout the Phase II field experiment.

Representatives from the US Army Engineer District, Los Angeles, who participated in the CODAR mobilization/demobilization exercise, were Messrs. Don Cords, Brian Emmett, and Barry Willey.

Dr. James H. Allender and Mr. Larry D. Brooks from Chevron Oil Field Research Company, La Habra, California, assisted by providing data from Platform Grace.

Extensive assistance in developing, using, and interpreting the CODAR system was provided by CODAR Ocean Sensors, Ltd., and CODAR Technologies, Inc. Principal contributors were Drs. Donald E. Barrick and Belinda J. Lipa, and Messrs. Jimmy Isaacson and Pete Lillyboe.

Critical assistance and support were provided by the Pacific Missile Test Center, Point Mugu, California, during the Phase I experiment. Key contributors were Messrs. Richard Dixon and Robert Mackie and Mrs. Lisa Sherwood.

Dedicated assistance in arranging a flight plan, coordinating dates, and determining optimum weather forecasts for overflights with the Surface Contour Radar was provided by Dr. Edward Walsh, National Aeronautics and Space Administration, Goddard Space Flight Center, Wallops Island Flight Facility, Wallops Island, Virginia.

COL Dwayne G. Lee, EN, was Commander and Director of WES during publication of this report. Dr. Robert W. Whalin was Technical Director.

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COASTAL OCEAN DYNAMICS APPLICATIONS RADAR (CODAR) REMOTE SENSING DEMONSTRATION PROGRAM

PART I: INTRODUCTION

Background

1. In January 1985, the US Army Engineer District, Los Angeles (SPL), with the assistance of the US Army Engineer Waterways Experiment Station's (WES's) Coastal Engineering Research Center (CERC), proposed a series of remote sensing demonstration projects for coastal California (US Army Engineer District, Los Angeles 1985). The program was designed to provide an opportunity to demonstrate the utility of existing and emerging remote sensing techniques for operational data acquisition in support of Corps field office needs. Demonstration projects were selected based on planned or ongoing SPL project needs and the unique opportunities provided by the Coast of California Storm and Tidal Waves Study (CCSTWS) and the Oceanside Experimental Sand Bypassing System monitoring program for high quality benchmark data to compare with the remote sensing information. The demonstrations also apply to various data needs in all coastal districts.

2. The proposed program was focused on data needs in the areas of wave climate and beach and nearshore bathymetry. For each data area, the proposed remote sensing data acquisition was designed to: (a) demonstrate operational capability, (b) establish cost effectiveness, (c) complement data acquisition already planned, and (d) train SPL personnel in the remote sensing technology. At the conclusion of the program, the Corps of Engineers would have several new operational methods of coastal data collection.

3. Three remote sensing techniques were selected for demonstration. Shore-based, X-band imaging radar has potential for providing nearshore wavelength and direction; a shore-based, high-frequency radar known as the Coastal Ocean Dynamics Applications Radar (CODAR) has potential for providing the full wave height directional spectrum; and an airborne laser mapping system may provide fast and accurate bathymetric surveys.

4. After extensive review by SPL, WES, and the US Army Corps of Engineers (USACE), it was decided that each of the techniques would be demonstrated independently. The CODAR portion of the proposal was approved by the

Chief, Operations and Readiness Division, Directorate of Civil Works, USACE, in August 1985. The program, funded over a 3-year period, was entitled the CODAR Remote Sensing Demonstration Program (CRSDP).

5. The CODAR system is a high-frequency, ground-based radar with potential for acquiring directional wave spectra at distances of up to 20 miles (32 km) from shore. Its potential strengths include:

- a. Reliability. Since all components of the system are located on land, the system can be protected, inspected, and serviced without concern for the ravages of ocean waves, although vandalism is a potential concern.
- b. Portability. The system is relatively compact and portable.
- c. Ease-of-Use. The system includes user-friendly software to give users easy control over such things as the data collection scheme and special output displays.
- d. Economy. Because the system is relatively protected, easily accessible, and uses many standard hardware components, it has potential for economical operation.

6. CODAR was developed originally to measure surface currents. The original antenna design used separate antennas for transmitting and receiving. The receiving antenna system was composed of three or four independent whip antennas which acted much like a radio direction finder. This system was used to collect current information in a variety of locations (Barrick and Lipa 1979a). This system was, however, unable to extract direction information for wave measurements, leading to the development of the compact, crossed-loop system currently in use (Barrick and Lipa 1979b).

7. The more difficult problem of extracting information on surface waves from high-frequency radar return has received extensive treatment (Barrick 1972, 1977; Barrick and Lipa 1979b, Lipa 1977, and Lipa and Barrick 1980). This process required additional assumptions and complex processing of second-order information in the radar return. Success in acquiring wave information with a crossed-loop CODAR system was reported by Lipa and Barrick (1981, 1982) and Lipa, Barrick, and Maresca (1981). Several other programs to develop high-frequency radar for current measurement are ongoing outside the United States (Wyatt et al. 1986, Prandle 1987, Wyatt 1987).

8. WES purchased a CODAR system in 1983 because of its potential for measuring coastal waves and currents. The system is described in more detail in Part II of this report. WES used the system in conjunction with a leased system to measure currents in Delaware Bay in 1984 (Driver, in preparation;

Porter et al. 1986). The Delaware Bay experiment coincided with extensive National Oceanic and Atmospheric Administration (NOAA) measurements using in situ gages. NOAA was a joint participant with WES in the CODAR exercise. CODAR measurements compared reasonably well with in situ measurements, but direct comparisons were difficult. CODAR averages over a spatial area on the order of 3 square miles (7.8 sq km) and measures currents within 3 ft (0.9 m) of the water surface, while in situ gages measure at a point in space and were located 10 ft (3.0 m) or more below the water surface for practical reasons.

District Needs for Wave Measurement

9. An assessment of Corps of Engineers District needs for wave measurement was needed as part of the CRSDP to demonstrate CODAR's potential for practical use. A summary of needs was developed with information from the districts participating in the CRSDP (Table 1). It is notable that wave direction is needed in virtually every wave measurement application.

Table 1

District Needs

Project	Data Requirements
Beach erosion studies	Nearshore wave height and direction
Structures design	Local wave height, period, and direction
Dredging operations	Wave height, period, and direction at dredge location
Locating and monitoring offshore disposal sites	Offshore wave height, period, and direction and vertical current profile
Legal proceedings	Accurate and reliable wave parameters

Plan of Study

10. The CRSDP was planned as a three-phase program. Phases I and II involved CODAR demonstrations at two separate field locations. Phase III was the technology transfer phase. A critical requirement for Phase I was a

minimum of one reliable directional measurement source offshore to compare with CODAR over at least a 2-month period. The large diameter wave buoys operated by the National Data Buoy Center (NDBC), NOAA, provided the only reasonable source. Of these, only one was sufficiently nearshore in southern California to be close to CODAR's coverage area. Because of NOAA's limited buoy inventory, there was no possibility for special buoy deployment under Phase I of CRSDP.

11. The Phase I experiment was conducted at the Pacific Missile Test Center (PMTC), Point Mugu, California, during April through July 1986. The Naval Civil Engineering Laboratory (NCEL) in Port Hueneme, California, was conducting a major field experiment in the same area 25 miles (40 km) offshore. The NOAA directional wave buoy and other sensors were deployed in the area as part of NCEL's project.

12. The Phase II experiment was planned to demonstrate the use of CODAR for estimating waves very near shore. The originally planned site was Oceanside, California, where several nearshore gages were already in place. However, the Phase I results indicated a need for very definitive offshore measurements as well as nearshore measurements in Phase II. The Phase II experiment was relocated to the FRF where additional offshore gages were deployed and exceptionally accurate nearshore instrumentation was already in place. The Phase II experiment occurred during September 1987 through March 1988.

13. Criteria against which the performance of CODAR would be judged were developed at the beginning of CRSDP. CODAR would be evaluated relative to the most accurate conventional gages available in each phase of CRSDP. The criteria were as follows: significant wave height within 10 percent, peak spectral wave period within 1.0 sec, and dominant wave direction within 10 deg. The significant wave height is defined as an energy-based wave height and is equal to four times the square root of total spectral energy. Peak period is defined as the period associated with the peak value in the energy spectrum, and the dominant direction is the direction corresponding to the peak period. It was recognized that, even under the best of circumstances, some fraction of the data would fail these criteria due to the statistical variability of ocean waves. However, the criteria are representative of the accuracy of conventional gages, and they provide a useful yardstick for comparison. Perspective on comparisons between CODAR and conventional gages

can be gained by intercomparing more than one conventional gage.

Organizational Structure

14. The general manager of the Remote Sensing Demonstration Program for Coastal Regions is the Operations and Readiness Division, USACE. The CRSDP was managed by WES. SPL provided a point of contact for the program. In addition to this management structure, a CRSDP Working Group was formed. The working group was tasked with reviewing and making recommendations on the planning, scheduling, execution, end products, and technology transfer of the CRSDP. Members were selected based on interest in the CRSDP and potential applications in their district areas. The SPL point of contact was a member. Remaining members represented the US Army Engineer Districts, Norfolk, Galveston, and Portland. The working group met five times, at critical points during the CRSDP, as detailed in Table 2.

Table 2

Summary of CRSDP Working Group Meetings

Date	Location	Major Agenda Items
13 Nov 85	Point Mugu, CA	Select Phase I field site. Define expectations from CRSDP for parameters, accuracy, coverage, comparisons, end products. Discuss technology transfer mechanisms.
5 Jun 86	Channel Islands Harbor and Point Mugu, CA	Discuss data collected to date. Review plans for data comparisons. Visit operational field site. Discuss initial plans for Phase II.
17 Dec 86	Oceanside, CA	Review Phase I results. Select Phase II field site. Review Phase II plans and expectations for data comparison, district familiarization, etc.
22 Oct 87	Duck, NC	Review preliminary Phase II results. Visit operational field site. Discuss plans for completing Phase II.
3 Jun 88	Washington, DC	Review district needs. Review Phase II results. Discuss and form conclusions about CODAR performance.

PART II: REVIEW OF WAVE SENSORS

NOAA Directional Buoy

15. The NOAA directional wave measuring buoy is a large diameter (33 ft (10 m) for Phase I, 10 ft (3 m) for Phase II), discus-shaped hull containing sensors that measure buoy heave (vertical acceleration) and pitch/roll (slope). Also on board are sensors for measuring wind speed and direction, barometric pressure, and air and sea temperature. Onboard processing of the heave/pitch/roll signals provides an estimate of the first five Fourier coefficients of the angular distribution of energy at each of 35 frequency bands. This is the same basic information that is provided by the CODAR system. From these coefficients, estimates of the nondirectional frequency spectrum and mean and principal wave directions are made. Typical information from the NOAA buoy is illustrated in Figure 1. Estimates of significant wave height, peak frequency, dominant direction, and mean frequency are also determined. In addition, the Fourier coefficients can be used to compute the full directional spectrum. Accuracies for significant wave height are reported to be 5 to 10 percent (Earle, Steele, and Hsu 1984). A detailed description of the buoy, processing procedures, and products is provided by Steele, Lau, and Hsu (1985).

CODAR

16. The CODAR high-frequency radar system was designed to be a portable, shore-based radar for monitoring surface currents and waves. The system has been described in detail in several publications in terms of basic principles (Lipa and Barrick 1986), applications (Driver, in preparation; Lipa, Barrick, and Maresca 1981; Spillane et al. 1986), and operational procedures (CODAR Handbook 1987). For purposes of this report, the following information should allow an understanding of the results and subsequent discussion of the CRSDP.

17. The CODAR system is unique in the field of high-frequency radar due to the compact, three-element, crossed-loop antenna structure (Figure 2). The loop system has been improved over the last 4 years, but the basic principles and analysis techniques described by Lipa and Barrick (1983) remain unchanged. Field experience has shown that the antenna should be placed close to the

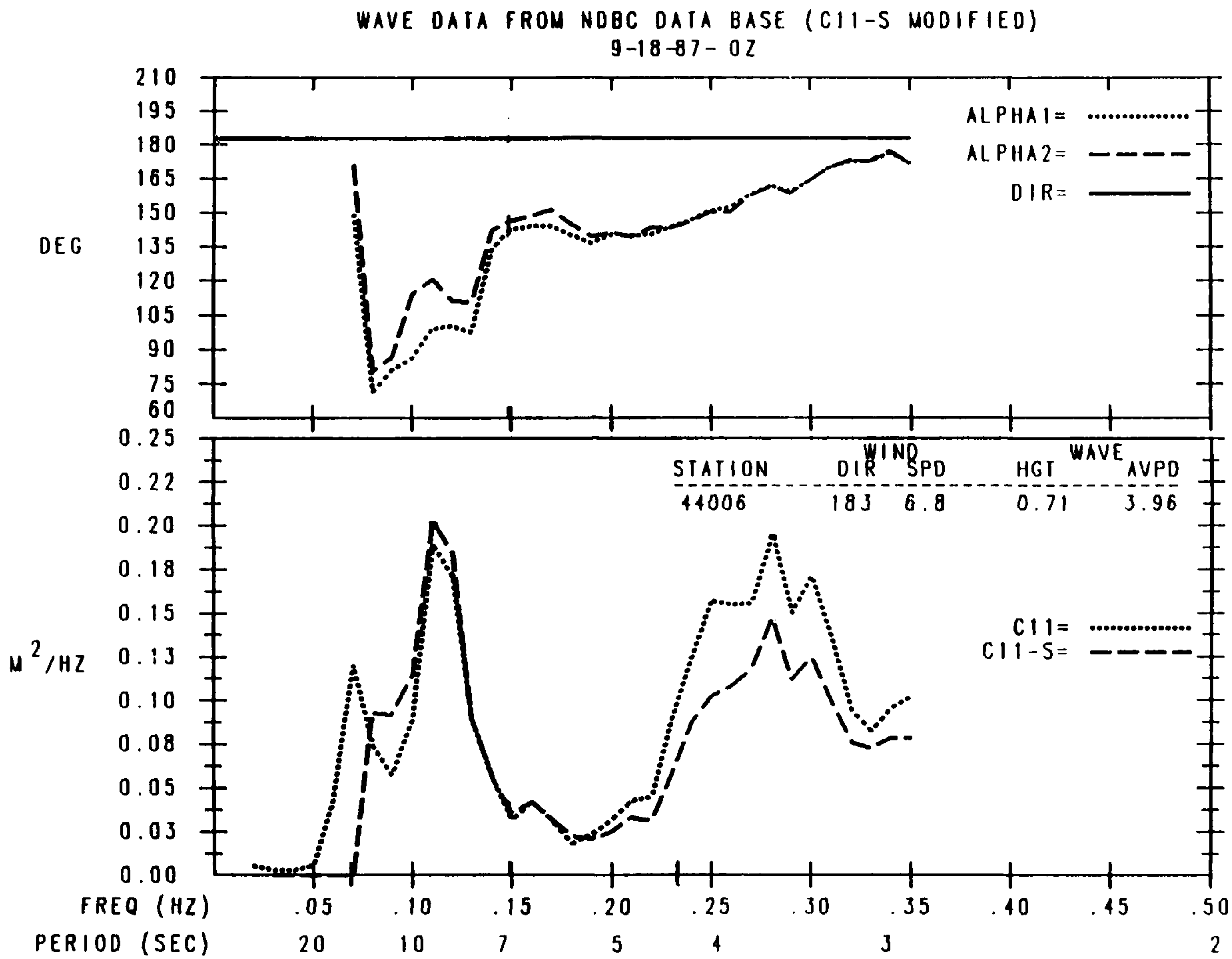


Figure 1. Typical information from a NOAA directional wave measuring buoy (lower plot, nondirectional wave height spectrum (C11, heave generated; C11-S, slope generated); upper plot, two measures of mean wave direction (dashed lines) and wind direction (solid line))

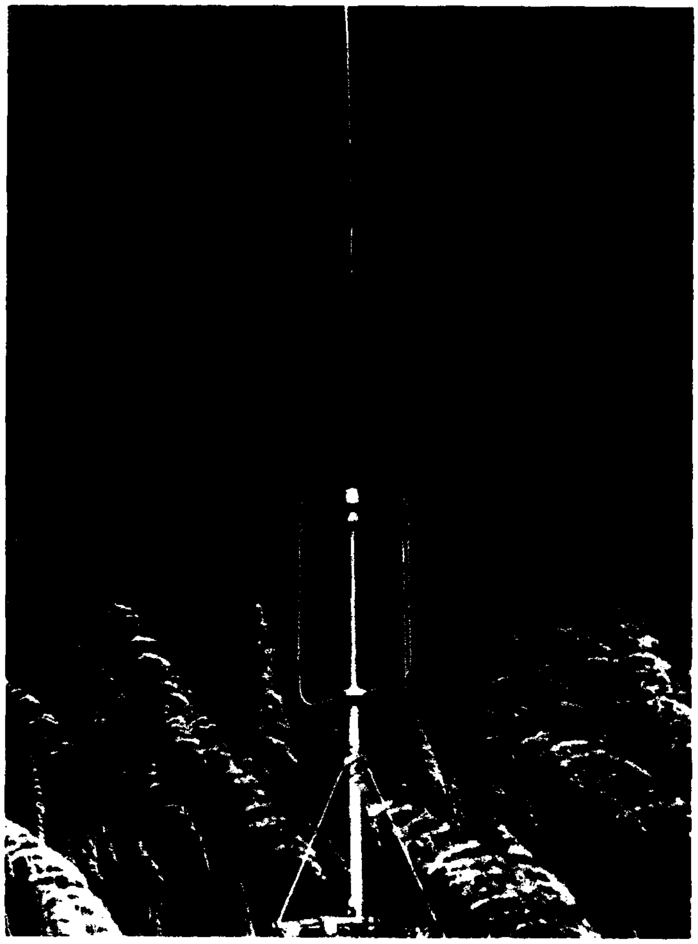


Figure 2. CODAR crossed-loop antenna system

water's edge and at an elevation as low as possible to ensure the strongest return. These criteria are generally best met by placing the antenna on the first dune line. The antenna is connected by cable to a nearby shelter housing the system electronics. The shelter should be within 300 ft (91 m) of the antenna. Electronic equipment in the shelter includes the transmitter and receiver, a Digital Equipment Corporation (DEC) Model PDP 11/23 minicomputer, a 9-track Cipher tape drive, a DEC LA50 printer/plotter, and a system video monitor. The total electronics package fits into two shock-mounted shipping boxes, each measuring about 3 ft (0.9 m) high, 2 ft (0.6 m) wide, and 2 ft (0.6 m) deep (Figure 3). The entire system is controlled by user-friendly software that allows the user to set various collection parameters such as sampling interval, range cells processed, and tape storage options (all raw data, processed data only), and to choose from a variety of display options.

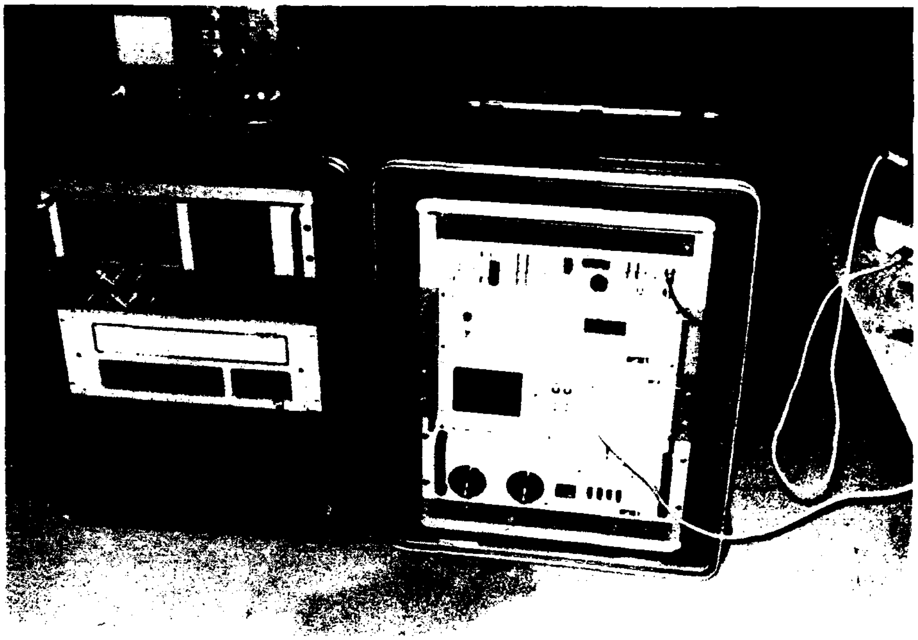


Figure 3. CODAR electronics package

The system also features an automatic restart in the event of a power failure.

18. CODAR transmits a 25.4-MHz signal, a portion of which is returned to the antenna by backscattering from the rough ocean surface. The system measures the amount of the return at each of the three elements of the antenna structure and uses this information to compute the sea echo Doppler spectrum. This spectrum is characterized by two separate regions corresponding to differences in the backscatter process (Figure 4). The first-order region is the most prominent and generally exhibits two large spikes that represent first-order Bragg scattering. Processing of this region yields information on surface currents (Driver, in preparation). The second-order region surrounding these spikes contains the wave information.

19. The return is range-gated into cells (the number of which is user selectable, up to a maximum of 76) having a radial width of 0.74 mile (1.2 km) (Figure 5). Doppler spectra from successive range cells are generally consistent in shape although the return signal decreases with distance from shore (Figure 6). Thus, although some signal is returned from distances of 20 miles (32 km) or more, the spectrum at these ranges often does not contain the second-order region required for wave processing.

20. Since CODAR uses the same antenna for transmitting and receiving, both processes cannot occur simultaneously. The finite time required for

Figure 4. Example of sea-echo Doppler spectrum for a single CODAR range cell (cross-batched portion represents first-order region surrounded by second-order continuum)

signal transmission leads to a loss of information, due to a lack of return signal, for an area within 1.5 miles (2.4 km) of the antenna. A loss of data is also experienced for the area near the coastline. Signal attenuation resulting from the coast generally eliminates information in an area extending roughly 10 deg from shore on both sides of the CODAR site. Figure 7 shows the resulting range cell limits, indicating that CODAR covers a large annulus but excludes the breaker zone. CODAR processing requires information from the entire range cell and cannot selectively isolate a particular direction for processing. Azimuthal gating of this nature could be accomplished with a much larger, multielement phased array antenna system, but this would defeat an original objective of CODAR development for a compact system.

21. Signal processing begins automatically after data collection is completed. The period for collecting data is user selectable, but typically 36 min is needed for stable results. Processing a 36-min data record takes about 50 min with the present computer. Hence, data can be collected no more frequently than every 90 min.

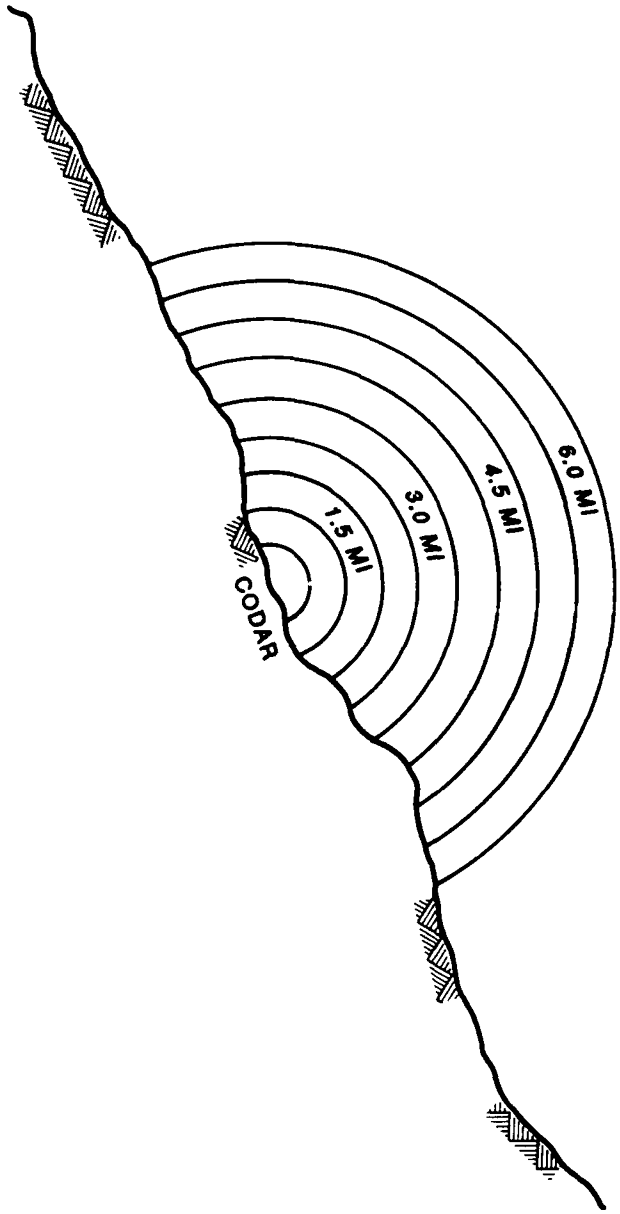


Figure 5. Typical CODAR range cells

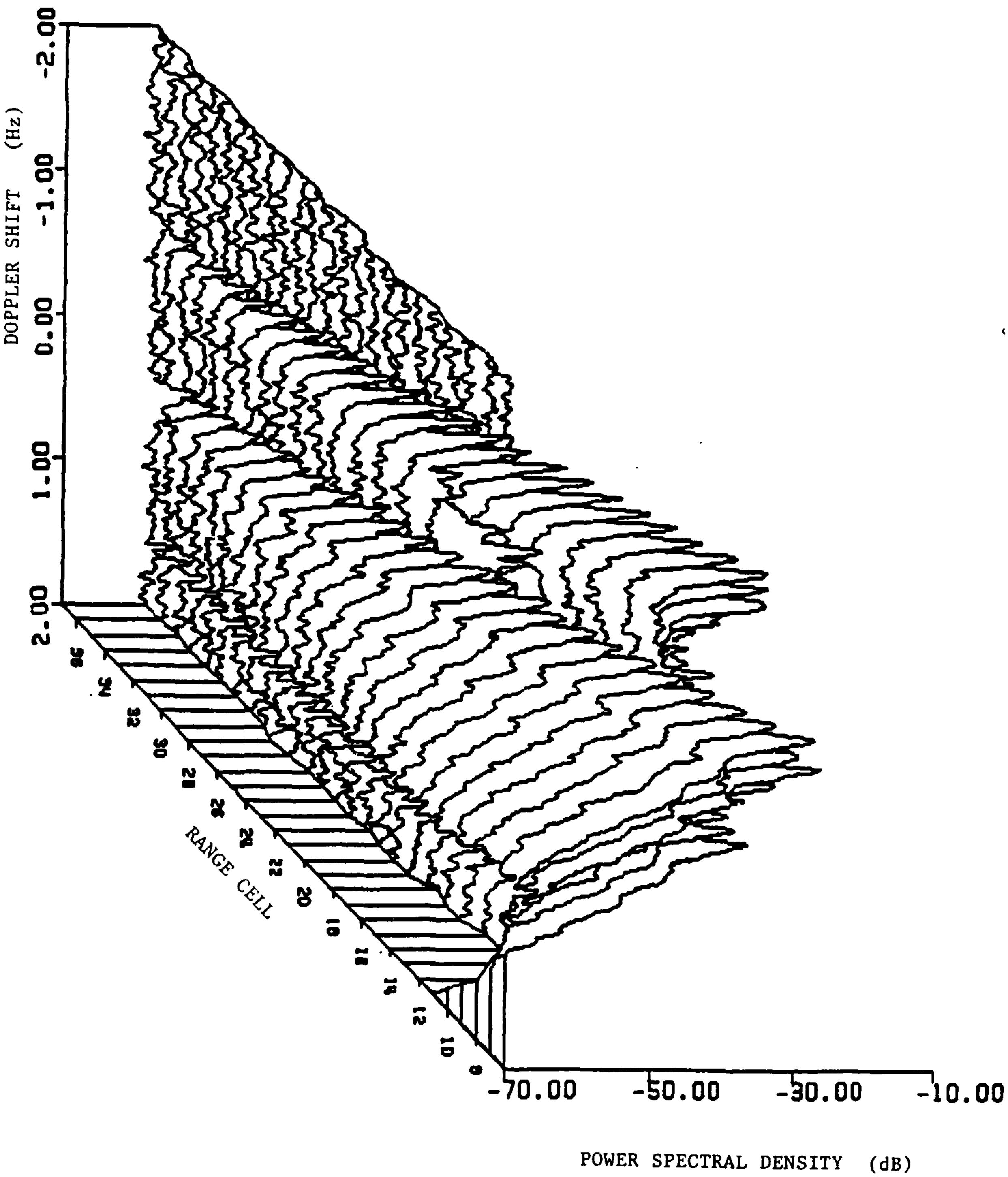


Figure 6. Example of a three-dimensional plot of sea-echo Doppler spectrum

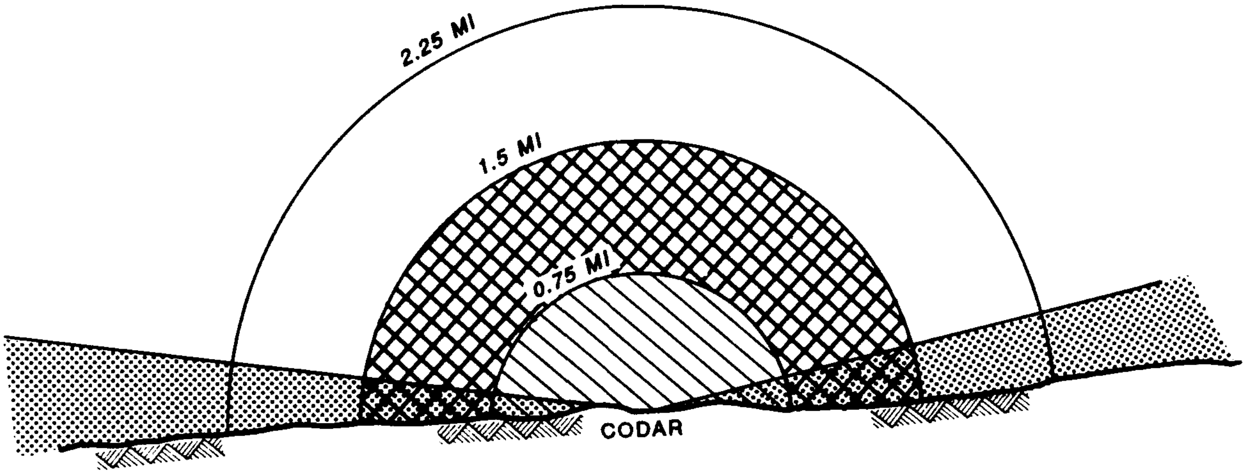


Figure 7. Graphic representation of CODAR nearshore limitations (shaded areas provide no information due to system timing and signal attenuation)

22. Processing of the second-order region of the Doppler spectrum provides information similar to that provided by the heave/pitch/roll buoy, including the first five Fourier coefficients of the angular distribution of energy at 19 frequency bands, estimates of the nondirectional frequency spectrum, mean wave direction, significant wave height, peak frequency, and dominant direction. Figure 8 illustrates a nondirectional spectrum and mean direction for each frequency band. A full directional distribution can also be computed. This information is available for each range cell. The user can elect to process each range cell individually or combine two or more for an estimate of the average wave conditions over a larger area. The assumption here is that the wave conditions are homogeneous over the averaged range cells. The range cells selected for processing are hereafter referred to as the CODAR coverage area.

Waverider Buoy

23. The Waverider nondirectional wave measuring buoy is a 3-ft- (0.9 m) diam sphere containing sensors that measure the vertical acceleration of the buoy. This information is telemetered back to a shore station where further processing provides estimates of the nondirectional energy spectrum, significant wave height, and peak spectral period. The Waverider buoy is a standard

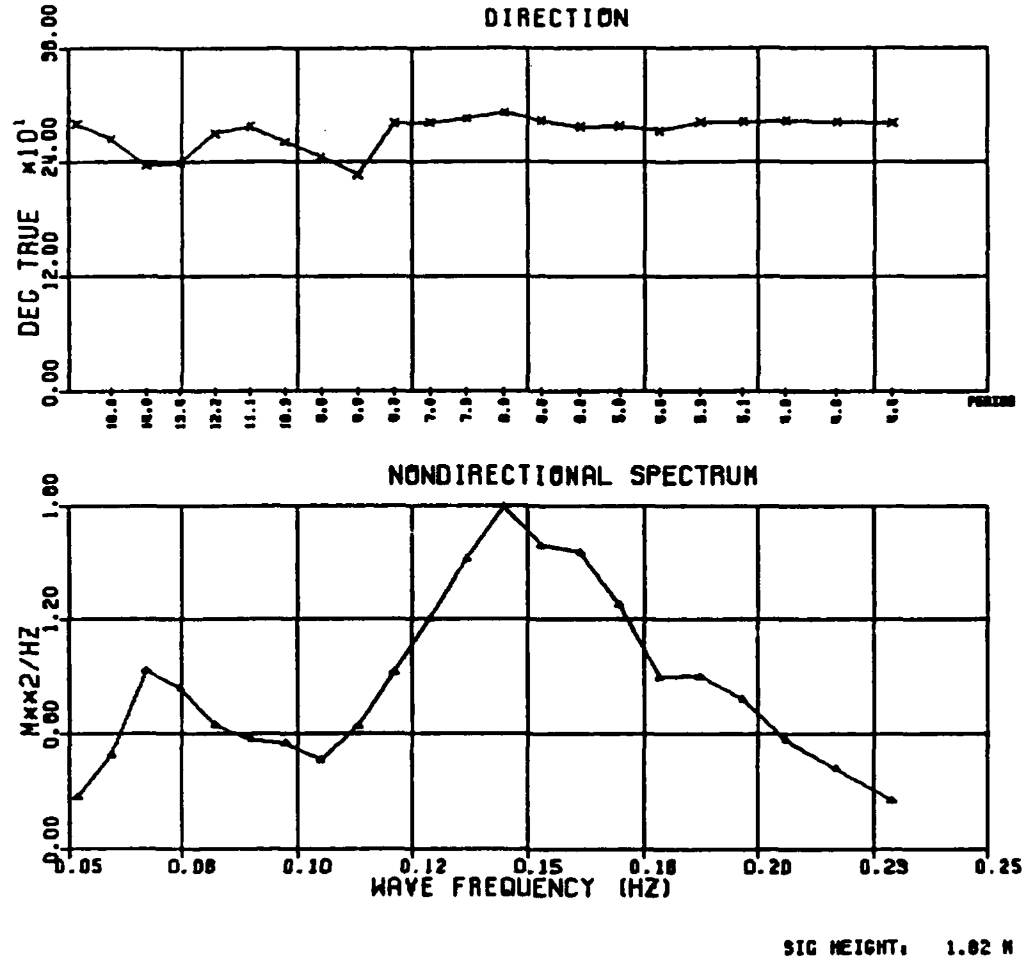


Figure 8. Typical information from CODAR (lower plot, nondirectional wave height spectrum; upper plot, mean wave direction)

sensor that is widely used for basic measurements of nonbreaking coastal waves.

Linear Array

24. The linear array directional wave measuring device, located at CERC's Field Research Facility (FRF), is a phased array of nine pressure sensors arranged in a line parallel to shore in approximately 26 ft (7.9 m) of water. The sensors, located about 2,500 ft (0.76 km) offshore, are spaced at various intervals ranging from 16 to 346 ft (5.0 to 105 m) and span a total of 850 ft (259 m). Each sensor measures the subsurface pressure fluctuations that result from passing surface waves. Processing of a combination of signals from several (four or more) sensors provides a directional wave spectrum with

a much higher directional resolution (15 deg for monochromatic waves) than that available from surface following buoys such as the NOAA buoy. In addition to wave direction, each sensor is capable of providing an estimate of the nondirectional energy spectrum, the significant wave height, and the peak spectral period. Detailed procedures for processing multielement array data are given in Davis and Regier (1977).

PART III: CRSDP PHASE I

Objectives

25. Phase I of the CRSDP was designed to demonstrate several of the unique capabilities of the CODAR system. The main emphasis was centered on a comparison of selected wave parameters as measured by CODAR and the NOAA buoy. In addition, CODAR's portability and ease-of-operation would be demonstrated by having personnel from SPL, after a short period of familiarization, demobilize the system and redeploy it at a new site. A third objective was to document the anticipated competitive costs associated with a long-term CODAR deployment field experiment.

Field Experiment

26. The establishment of a CODAR site takes a certain amount of advance planning to satisfy various system requirements. The chosen site must be equipped with a reliable source of electrical power (120 V), backup power if the primary source is prone to blackouts, and it must provide access to the dune/beach area. There should be an area, preferably on the top of the first duneline, for installation of the CODAR antenna. This area should be free of any structure (within a 300-ft (91 m) radius) that may cause interference with the transmitted/received signal, including large buildings and any vertical metallic structure such as a flagpole or another antenna. There must also be a building, or an area sufficient for locating a van or temporary structure, within 300 ft of the antenna for housing the system electronics. This facility must be climate controlled.

27. The experiment site chosen for Phase I was an isolated beach within the PMTC (Figure 9). The site met all of the system requirements, with a rented van (Figure 10) being brought in for the electronics. Although previous CODAR systems had been used to measure directional waves, the CSRDP was the first totally automated CODAR system for monitoring coastal waves. After system setup and checkout, data were acquired, processed, and stored on tape every 3 hr. This time interval is user selectable, from a minimum of 1.5 hr to a maximum of 24 hr. Operational requirements are minimal, involving periodic checks of system performance and magnetic tape changes. The 9-track

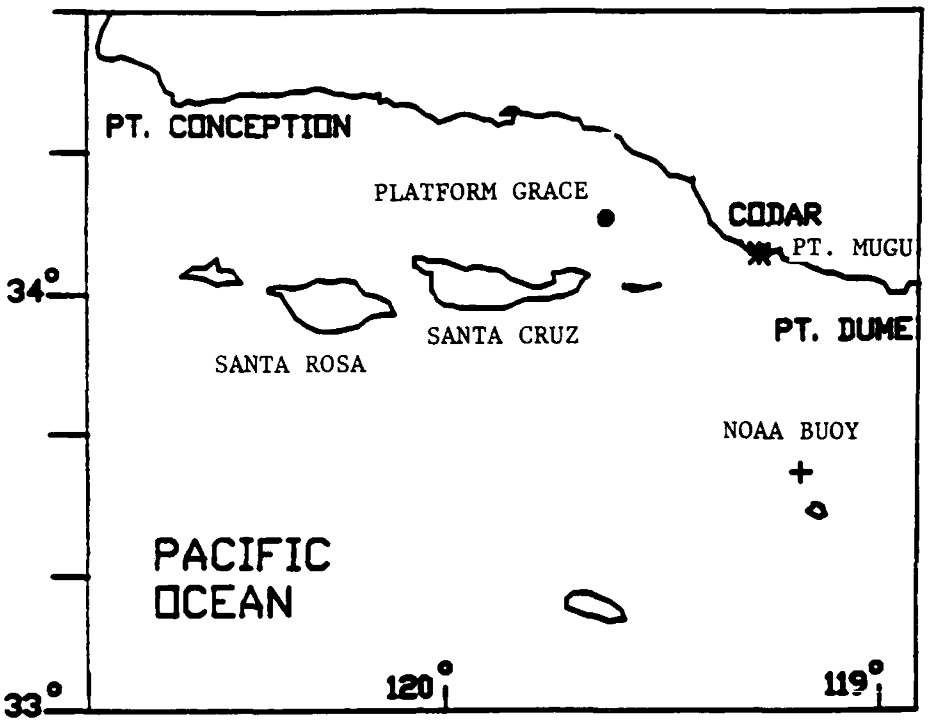


Figure 9. Location map for CRSDP Phase I, Point Mugu, California

Figure 10. Van used for housing electronics during Phase I

tapes are capable of storing 10 weeks of data but were changed on a weekly basis to allow quicker access to the data and to prevent a large amount of data loss should the tape drive experience problems. This invaluable assistance was provided by personnel from PMTC. The cycle continued for 2-1/2 months and was interrupted only twice, once during a CRSDP Working Group meeting and once when the tape drive failed to restart after a power outage. Four days of data were missed before the problem was discovered and fixed.

28. The familiarization of SPL personnel occurred on two separate occasions. On 2-3 June three SPL engineers were instructed in basic CODAR operational procedures, such as system power-up, performance monitoring, initiating data collection, changing tapes, and interpreting results (Figure 11). They were also provided with general information on the principles of CODAR operation. Then, at the conclusion of Phase I on 16 July, two of the three returned to complete the familiarization process which included shutting down the system, disconnecting all cables, dismantling the antenna, and readying the system for relocation (Figure 12). After completely vacating the site, the two engineers, with minimal guidance from CERC personnel, re-deployed the system at the site and initiated a data run. The whole process took less than 1 day. Satisfied that the familiarization objective was met, CERC personnel demobilized the system and prepared it for shipment to the Phase II location. Based on the experience gained in Phase I, estimates were made for the cost of removing CODAR from a site and redeploying it at another site within a typical district area. The total cost estimate was approximately $1,700, as detailed in Table 3. This estimate includes assumptions that the new site has already been reconnoitered and that electrical power is available in the general vicinity.

Data Analysis

29. The weekly CODAR data tapes were sent to CERC for further analysis and comparison. Data from the NOAA buoy were received on a monthly basis in the form of 9-track magnetic tapes containing hourly measurements of both oceanic (wave data, sea temperature, etc.) and atmospheric (wind, air temperature, barometric pressure, etc.) parameters. Only those data corresponding to the eight daily CODAR measurements were retrieved from the buoy tape. The buoy began experiencing problems in early July and was not fixed until

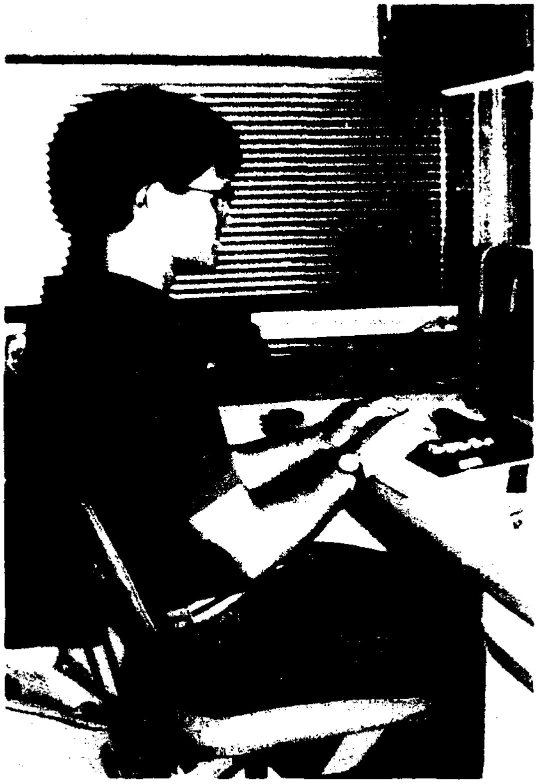


Figure 11. SPL personnel initiating a data run from system console

Figure 12. SPL personnel demobilizing CODAR antenna

Table 3

Estimate of Typical Costs for CODAR Redeployment

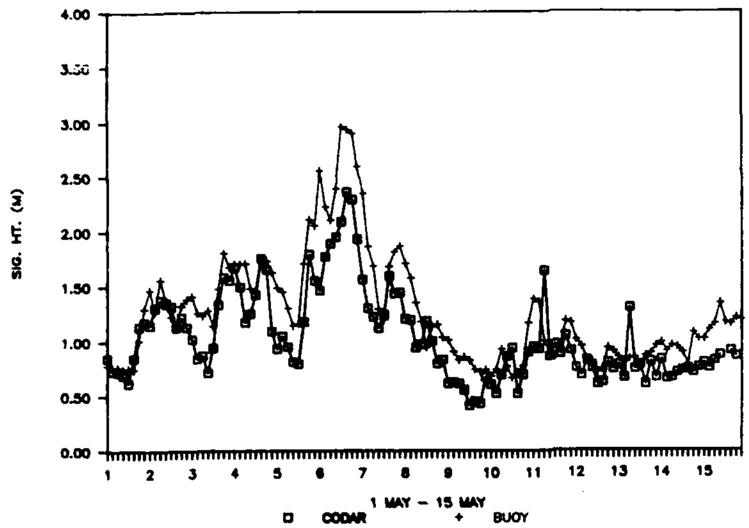
Item	Cost
Removal From Initial Site	
Travel to site (2 people × 0.5 day × $200/day)	$ 200
Demobilize system (2 people × 0.5 day × $200/day)	200
Travel/per diem (200 miles × $0.205/mile + 2 people × 1 day × $50/day)	141
Deployment at New Site	
Arrange for power at site	300
Travel to site/return to home office (2 people × 1 day × $200/day)	400
Deploy system (2 people × 0.5 day × $200/day)	200*
Travel/per diem to site and return to home office (600 miles × $0.205/mile + 2 people × $59)	241
TOTAL	$1,682

* Note: This cost does not include measurement of the antenna beam pattern and adjustment of gain settings which may be required at some sites (particularly sites with structures located within 300 ft of the antenna). This operation requires a boat and would add significantly to the cost. The range of experience provided by the two experiments in CRSDP is insufficient to assess this aspect of CODAR deployment.

17 July. Data for comparison purposes were, therefore, available only through the end of June. All sensor data were written to a master file for subsequent processing.

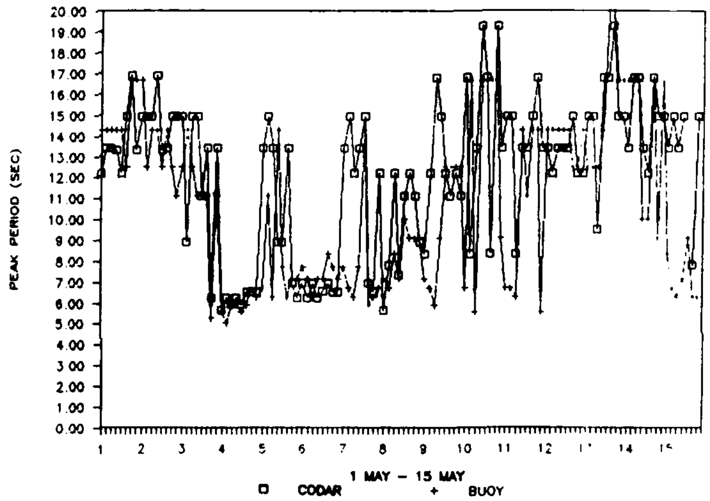
30. Statistical and graphical methods were used in comparing data from the two sensors. Weekly time series plots of the three parameters of interest were constructed to aid in the editing of spurious data (an integral part of any field data collection scheme) and to provide a visual estimate of how well the two data sets agreed (Figure 13). Additional plots for Phase I are given in Appendix A. During the comparison period of May-June, both sensors performed well, with CODAR collecting approximately 94 percent of the available data and the buoy collecting nearly 100 percent.

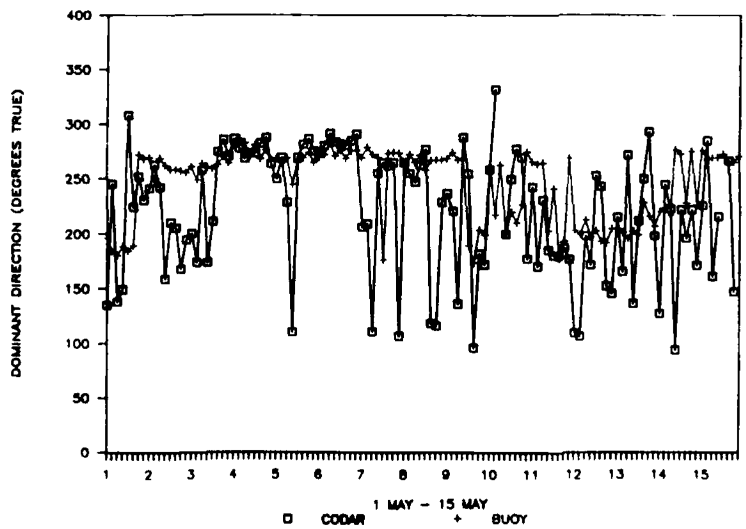
31. Scatterplots were created, and linear regressions were run to summarize each of the three parameters during the full Phase I experiment. Regression statistics are shown on each plot (Figure 14). Table 4 contains mean and standard deviation values of each parameter for all data and as a



a. Significant wave height

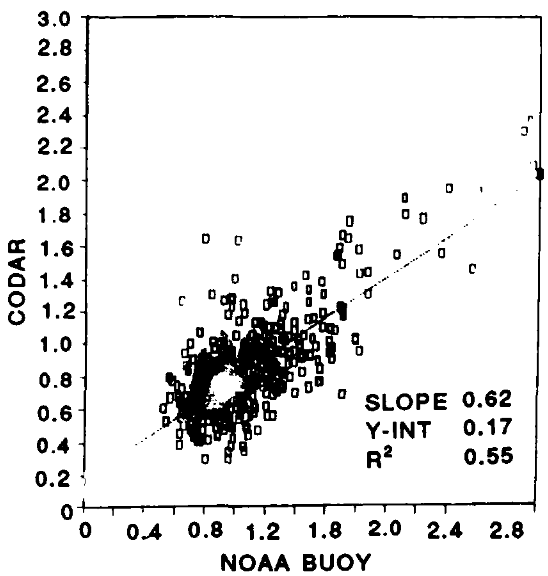
b. Peak period



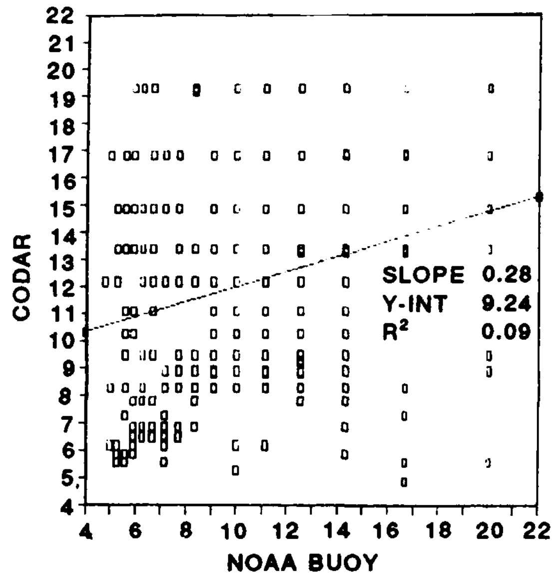


c. Dominant direction

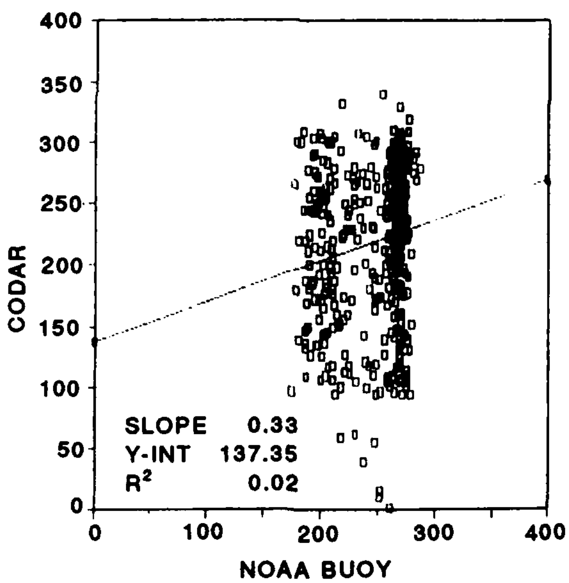
Figure 13. Example of time series plots for Phase I CODAR and NOAA buoy data



a. Significant wave height, m



b. Peak spectral period, sec



c. Dominant direction, deg T

Figure 14. Phase I scatterplot of CODAR/NOAA buoy data (total of 431 data points

Table 4

Phase I CODAR and NOAA Buoy Statistics*

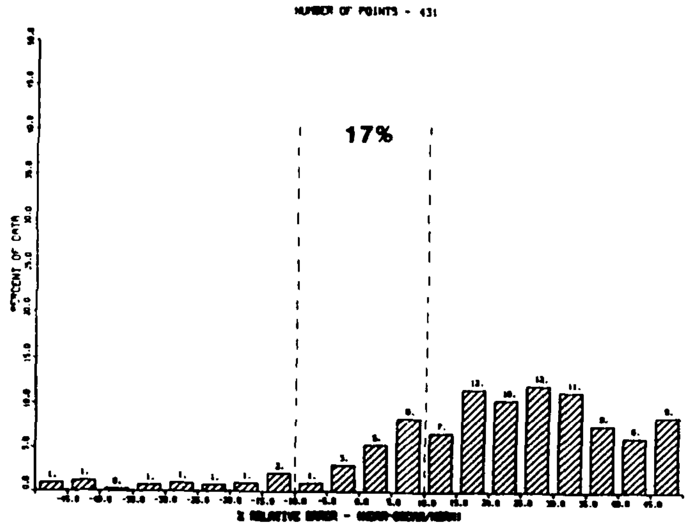
	Significant Height, m		Peak Period, sec		Dominant Direction, deg		Average Period, sec		Average Direction, deg	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
					All Data					
CODAR	0.84	0.31	12.36	3.54	231	132	9.82	2.74	248	116
NOAA	1.09	0.36	11.23	3.83	247	116	8.60	2.34	262	102
					$H_{mo} < 1$ m					
CODAR	0.70	0.21	12.67	3.52	228	134	10.19	2.77	239	124
NOAA	0.83	0.11	12.36	3.86	233	130	8.52	2.13	258	106
					1 m $< H_{mo} <$ 2 m					
CODAR	0.92	0.24	12.34	3.40	229	134	9.62	2.67	252	112
NOAA	1.26	0.22	10.33	3.51	259	105	8.77	2.56	265	99
					$H_{mo} > 2$ m					
CODAR	1.88	0.28	7.19	1.98	277	87	6.90	0.24	280	84
NOAA	2.47	0.33	7.32	0.50	273	91	7.07	0.36	273	91

* Number of observations = 431.

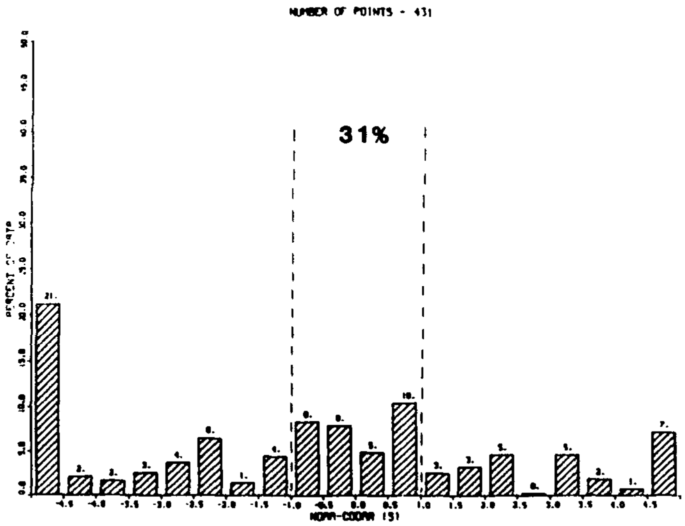
function of three significant wave height intervals. The mean values indicate that CODAR agrees more closely with the NOAA buoy during periods of low wave energy. The significant heights show some correlation, while the peak periods and dominant directions, which are inherently less stable than significant heights, exhibit very little correlation. One reason for the variability of peak periods and dominant directions is the presence of multiple wave trains with disparate peak periods. Multiple wave trains are common along US ocean coasts (Thompson 1980) and were frequently observed during this experiment.

32. To assess the accuracy of CODAR relative to the NOAA buoy, differences between simultaneous buoy and CODAR measurements were plotted in bar graph form (Figure 15). These graphs depict the percentage of observations for which the two sensor measurements agreed to within the specified limitations. The results indicate that, for significant wave height (Figure 15a), the acceptance interval of 10 percent was achieved only 17 percent of the time. The graph also shows that the buoy wave heights were larger than the CODAR wave heights (positive x-axis) 88 percent of the time. Several possible explanations for the observed differences are detailed below. The acceptance

a. Significant wave height



b. Peak spectral period



c. Dominant direction

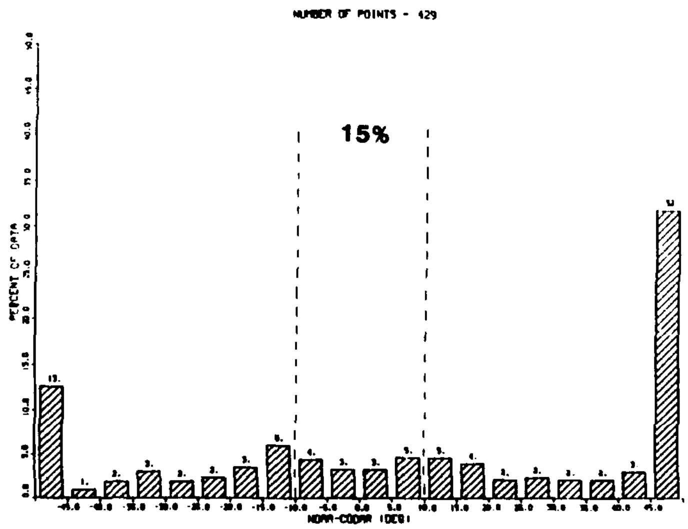


Figure 15. Bar graph showing differences in CODAR/NOAA buoy data (dashed lines encompass predetermined performance criteria with percent of data meeting the criteria)

interval of 1.0 sec for peak period (Figure 15b) was met approximately 31 percent of the time. There is, however, a large percentage (31 percent) of time when the difference in peak periods is greater than 4.0 sec. Differences in dominant direction (Figure 15c) were within specified acceptance levels 15 percent of the time. Again, the graph shows a large percentage (45 percent) of differences greater than 45 deg.

33. The Chevron Oil Field Research Company has an oil production facility, Platform Grace, located approximately 21 miles (344 km) west-northwest of Point Mugu. It is equipped with an environmental monitoring system that includes sensors for measuring wave height and period (Baylor wave staff), currents, and wind speed and direction. Chevron, as the owner of a similar CODAR system, was interested in the program and agreed to supply CRSDP with several weeks of data from Platform Grace. Significant height and peak period time series were plotted and compared with both CODAR and the NOAA buoy. The platform data were significantly different from both, and no further comparisons were made. Differences were attributed to the location of the platform.

Discussion

34. Although CODAR was less successful than anticipated in meeting the criteria established for acceptance for all three parameters, there are several complicating factors related to the demonstration site that must be recognized for a complete understanding of the data.

Strong surface currents

35. Surface currents that exceed 1.5 knots (75 cm/sec) severely hinder CODAR's ability to measure waves by smearing the second-order return signal to the extent that it is difficult or impossible to identify. For most of the demonstration period, a strong coastal current appeared to exist in a band that extended from roughly 3 to 10 miles (5 to 16 km) offshore. A persistent current of this strength was not anticipated but was evidenced by the loss of second-order return and by the strength of the radial component of the surface current sensed by CODAR. In an attempt to avoid the effects of this current, only CODAR data inside the 3-mile (5-km) range was processed and used in the comparison. Concerns about the unknown effect of Santa Cruz and Anacapa Islands intruding on the CODAR coverage area were also avoided by staying within the 3-mile (5-km) range. This solution to the surface current problem,

however, made direct comparisons between CODAR and the NOAA buoy, which was located 25 miles (40 km) offshore, more difficult. The effects of shoaling and refraction between the buoy and the CODAR coverage area, as well as CODAR's averaging over a nearshore annulus, may account for the smaller CODAR wave heights. Therefore, care must be taken in drawing conclusions from a comparison of wave parameters because the data comes from two geographically and bathymetrically different regions.

Channel Islands

36. The Channel Islands of Santa Rosa, Santa Cruz, and Anacapa lie due west of Point Mugu and the CODAR coverage area (Figure 9). These islands are known to have a sheltering effect on waves reaching the mainland. The extent of sheltering depends on the wave frequency and the direction from which the waves are coming. The predominant wave direction during the CRSDP, as measured at the buoy, was from the west. Hence, the CODAR coverage area was affected by island sheltering. The situation was further complicated by the fact that the buoy was far enough offshore to be beyond these effects. Thus, steps taken to avoid the effects of the strong coastal current introduced further uncertainty in the data comparisons because of island sheltering effects.

Wave climate

37. The data comparison effort in Phase I was affected by timing. The May-July period at Point Mugu is characterized by moderate swell wave energy with occasional mild storm events. Signficant wave heights of 1 to 3 ft (0.5 to 1.0 m) are typical as evidenced by the time series plots which indicate that, during the 2-month period, the buoy significant wave height exceeded 5 ft about 10 percent of the time. Spectra from both the buoy and CODAR obtained during the experiment often lacked the strong, dominant peaks that would be expected during more severe seasons. Thus, peak frequency and direction parameters were naturally more variable than they would be during the winter season.

Ship traffic

38. Large ships traversing the CODAR coverage area present a special problem for the CODAR system. The ship provides an excellent hard target, and its movement causes a spurious Doppler shift in the return signal, often resulting in a large spike in the sea-echo Doppler spectrum. This spike translates into an anomolously high wave height and can also result in erroneous

direction measurements. This effect is difficult to document without direct observation of passing ships, which is impractical during long-term deployments. Ship traffic was not a major concern at the 3-mile (5-km) range at Point Mugu, but a small fraction (<2 percent) of the data runs were questionable for reasons attributed to ship traffic. Ships are potentially a major concern at some sites where CODAR might be used.

39. Because of the complicating conditions outlined above, primarily the current-induced constraint of staying within 3 miles (5 km) of shore, it was difficult to draw definite conclusions about the accuracy of CODAR during Phase I of the CRSDP. The unanimous conclusion of the CRSDP Working Group after completion of Phase I was that a more definitive demonstration was needed in Phase II. Requirements for the Phase II site included minimizing, and possibly eliminating, complicating factors such as offshore islands and strong surface currents. At a minimum, a proven source of directional wave data, such as a NOAA buoy, should be deployed within the CODAR coverage area so that direct comparisons can be made. Additional sensors would add to the validity of the demonstration.

40. Phase I was successful in meeting several operational objectives of the CRSDP. Reliability over an extended deployment period was demonstrated by the fact that CODAR operated virtually uninterrupted for 11 weeks. Ease-of-use was demonstrated by both SPL and PMTC personnel. Costs associated with removal and redeployment of a CODAR system compared favorably with more conventional systems for wave measurement. These factors supported the decision to conduct a more comprehensive demonstration.

PART IV: CRSDP PHASE II

Objectives

41. The difficulties associated with clearly validating CODAR's capability to measure waves during Phase I made the Phase II experiment especially critical in the demonstration process. To meet the original objectives of the CRSDP and to best comply with the definitive test recommended by the CRSDP Working Group, the Phase II demonstration site was changed from its original location of Oceanside, California, to CERC's FRF in Duck, North Carolina (Figure 16). The FRF satisfied many of the requirements as part of its routine data collection effort, including data from several nearshore directional wave gages and a nondirectional Waverider buoy located approximately 4 miles (6.4 km) offshore. In addition, the FRF staff and resources are invaluable to the success of any coastal experiment.

42. The plan called for the deployment of a NOAA directional wave measuring buoy at a location within the CODAR coverage area. This buoy would be the primary instrument against which CODAR-derived offshore directional wave data would be compared. Two additional Waverider buoys were also planned to lie within the CODAR coverage area at locations north and south of the NOAA buoy (Figure 17). These buoys were funded by the Corps of Engineers Remote Sensing Research Program and were intended to provide much needed information on the spatial homogeneity of the wave field at any point in time. This information is critical to an evaluation of CODAR's capabilities. The Waveriders would also provide redundant wave height and period data for comparison purposes. In an effort to provide a strong measure of credibility to the CRSDP results, plans were made for the National Aeronautics and Space Administration (NASA), Wallops Island Flight Facility (WIFF), to fly over the CODAR coverage area with the Surface Contour Radar (SCR) (Walsh et al. 1985). This instrument is a widely accepted source of high-resolution, directional wave data that would have provided useful, although limited (due to plane costs/hour), comparison data. Unfortunately, a combination of inclement weather and schedule conflicts prevented the SCR from making the planned flight.

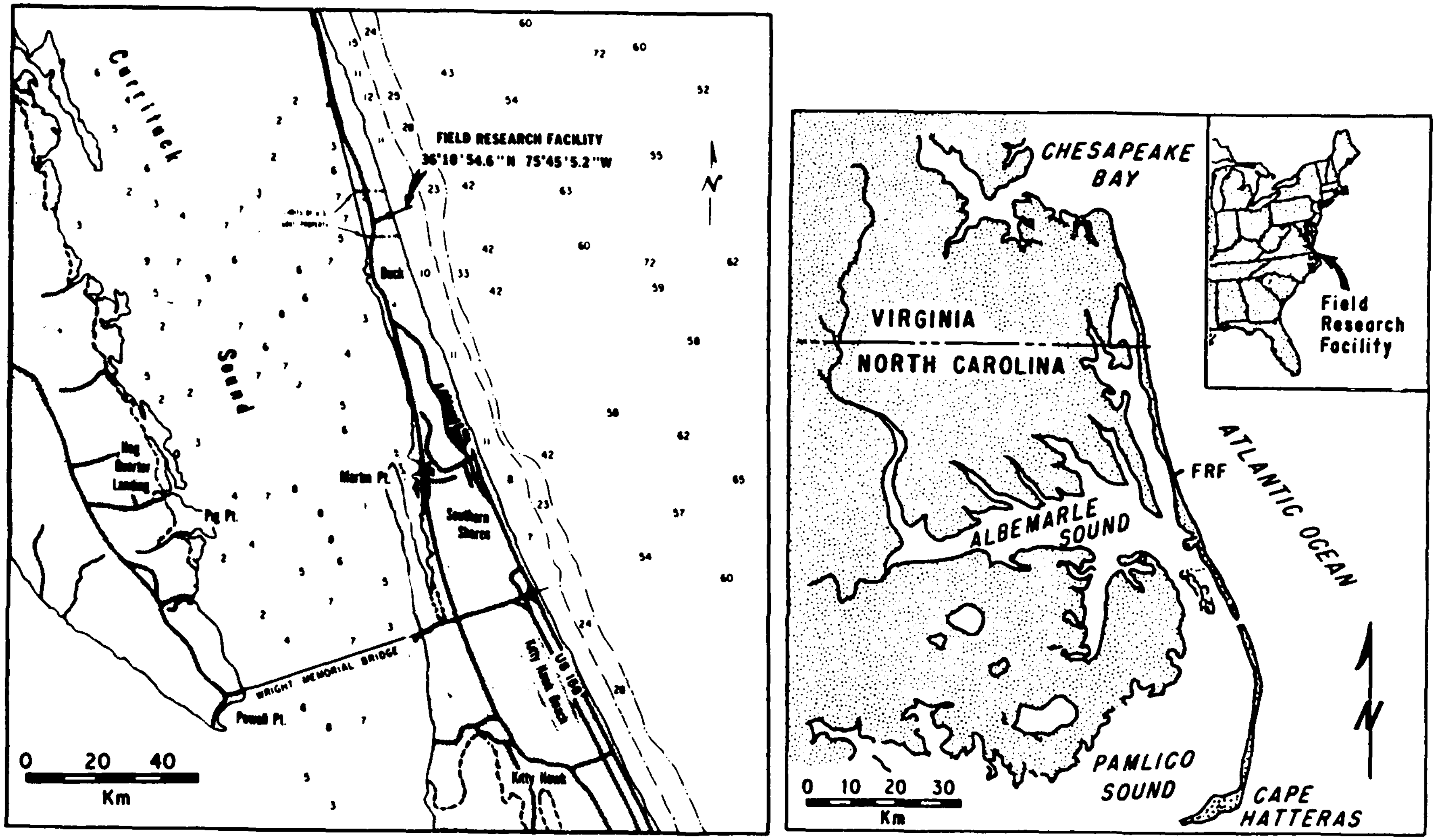


Figure 16. Location map for CRSDP Phase II, Duck, North Carolina

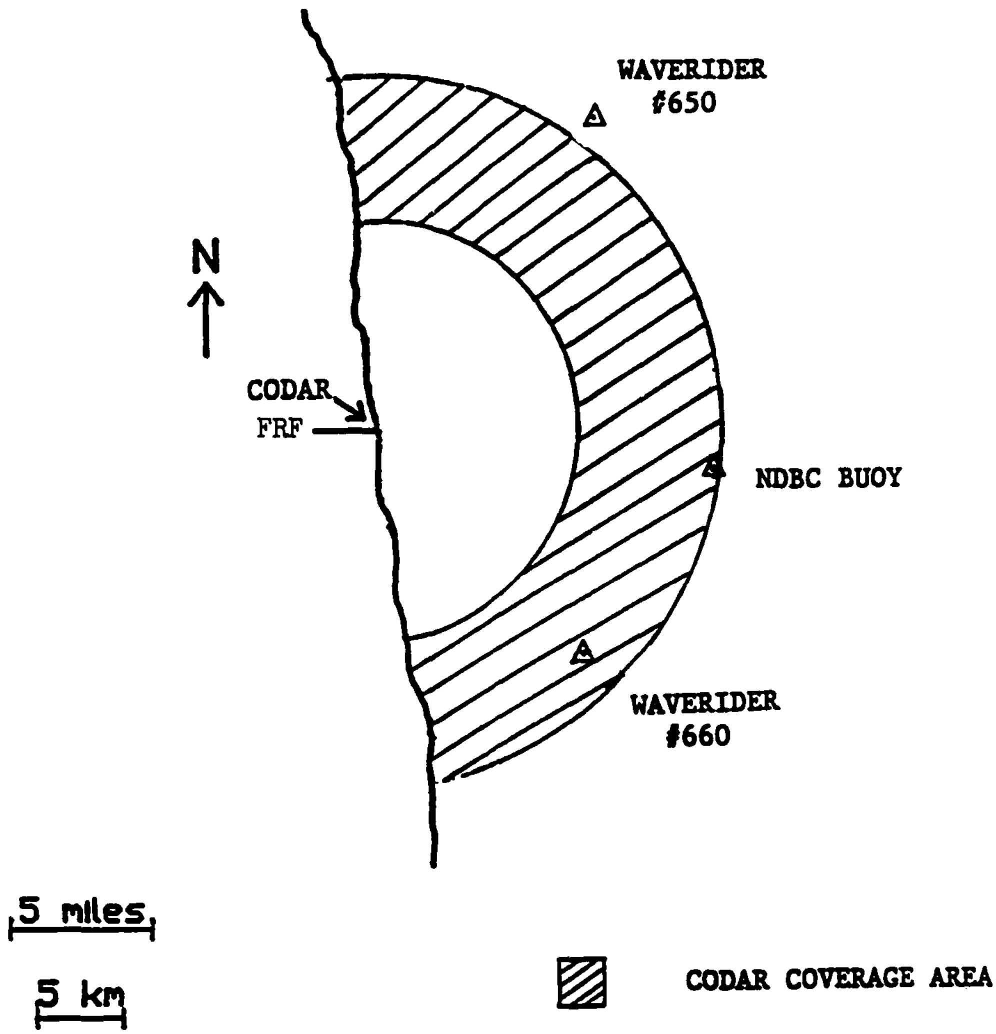


Figure 17. CRSDP Phase II offshore instrumentation

Field Experiment

43. CODAR was set up at the north property line of the FRF in mid-September 1987 while, at the same time, the NOAA and Waverider buoys were deployed at their preselected positions. CODAR was programmed to acquire data at 3-hr intervals to coincide with the routine FRF data collection. The NOAA buoy data were collected and processed by the NDBC and forwarded to CERC in the form of hardcopy tables, graphs, and monthly magnetic tapes. Waverider data were collected and analyzed by the FRF staff. As in Phase I, CODAR data were again recorded on 9-track tape, but the addition of a modem allowed communication and data retrieval from CERC headquarters in Vicksburg, Mississippi. This direct line of communication eliminated the need for frequent

tape changes and allowed greater flexibility and quicker access to the data.

44. The data collection effort was originally designed to end on 30 November 1987. However, the NOAA buoy began experiencing data transmission problems on or about 11 October and remained nonoperational until repairs could be effected on 2 December. Because of these problems, the working group decided to extend the period for collecting data to mid-February 1988. This extension would guarantee that a wide variety of wave conditions, from low energy to high energy winter storms, would be encountered.

45. CODAR operated continuously throughout the experiment with the exception of the 1-week period of 13-20 October when the transmitter experienced problems with electrical shorting. This problem was fixed by personnel from CODAR Ocean Sensors, Inc.

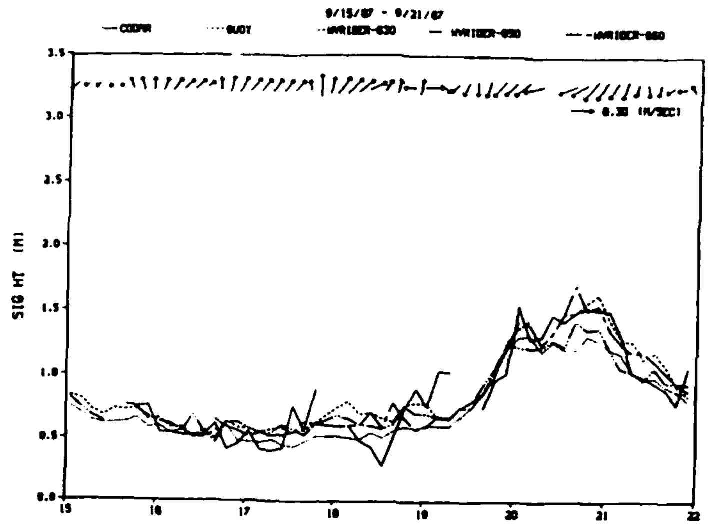
Data Analysis

46. Data analysis for Phase II was basically the same as that for Phase I. Parameters of interest were significant wave height, peak spectral period, and dominant direction; and the criteria for CODAR acceptance were set at the same levels as in Phase I. A total of 14 weeks of NOAA buoy data and 20 weeks of CODAR and Waverider data were available for comparison. A wide range of conditions was encountered, providing what is almost certainly the largest and most diverse body of CODAR wave data available for comparison purposes.

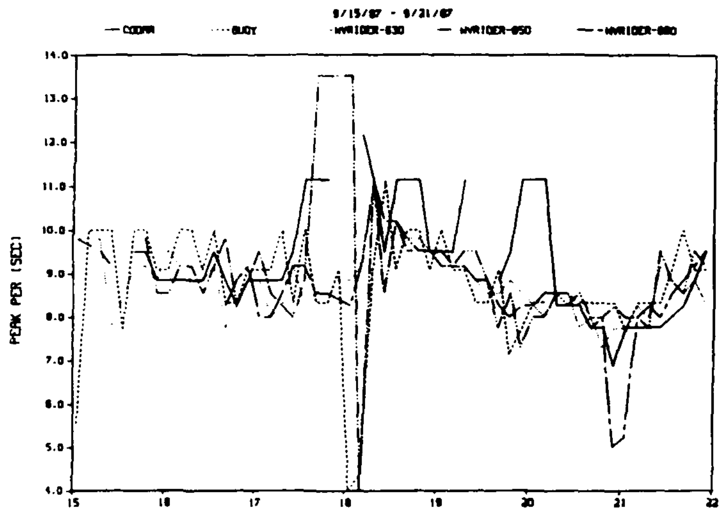
47. The data were subjected to both statistical and graphical analysis procedures to document sensor performance and to show how well individual sensors agreed with one another. Weekly time series plots of the parameters of interest were again used to edit out obvious spikes and jumps and to provide some visual indication of agreement (Figure 18). Complete time histories for the Phase II experiment are provided in Appendix B. In addition to peak period and dominant direction, mean values of these parameters were also routinely computed (Figure 19). Mean parameters are inherently more stable than peak parameters and can provide useful information under certain circumstances. However, peak period and dominant direction are the parameters most routinely used in the Corps, and they are the only ones fully included in this report.

48. Scatterplots were created, and linear regressions were run for all

a. Significant wave height



b. Peak spectral period



c. Dominant direction

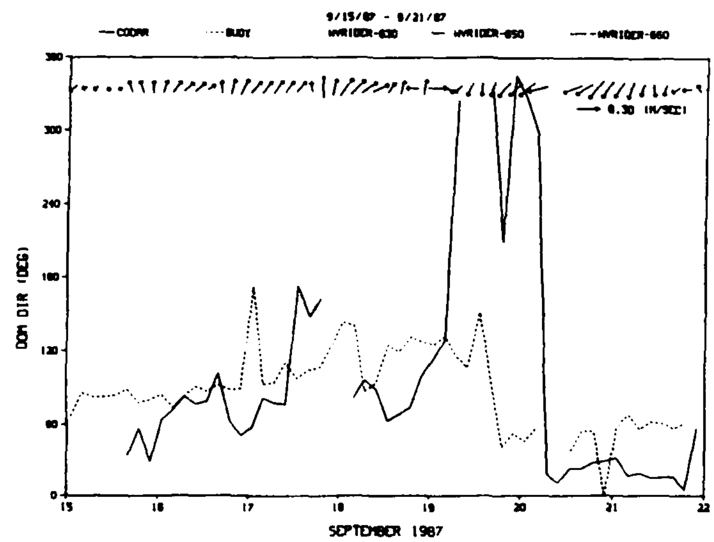


Figure 18. Example of Phase II time series plots for all available sensors

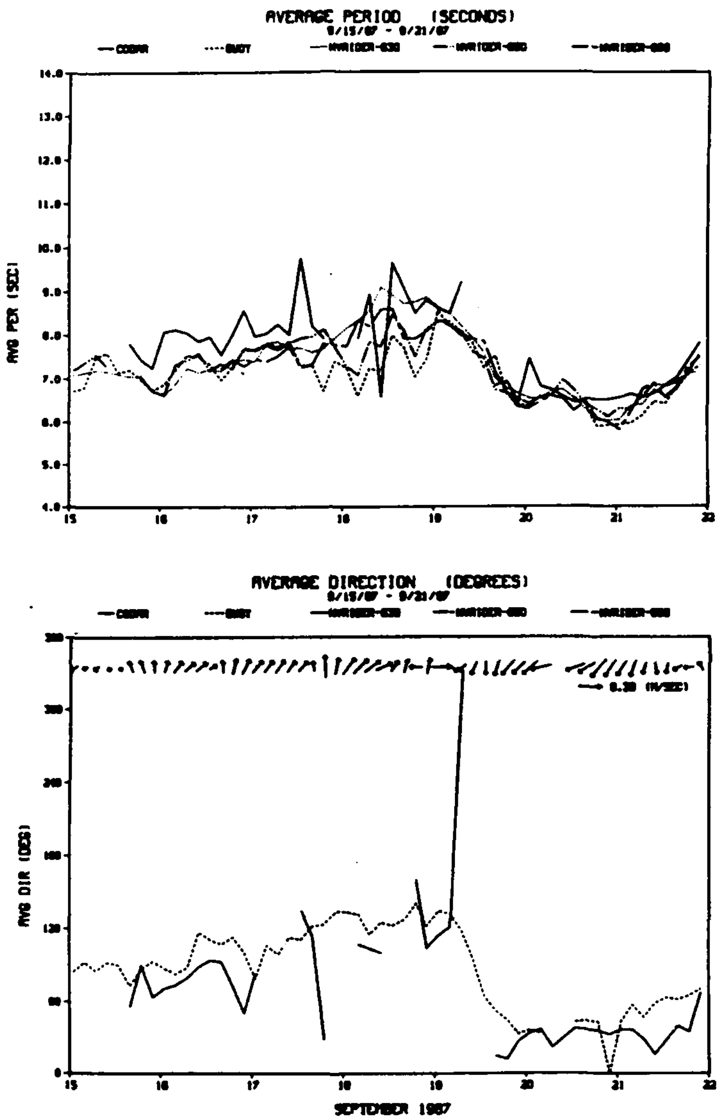


Figure 19. Example of Phase II time series plots of average period and direction (arrows indicate wind speed and direction measured at the NOAA buoy)

possible sensor pairs during the full Phase II experiment. Tables 5-10 provide mean and standard deviation values for each sensor pairing, including all coincident values and three significant wave height intervals. Tables 5-7, which show the statistics of sensor pairs involving CODAR, indicate, as did Phase I statistics, that CODAR shows better agreement with conventional sensors during times of low significant wave height.

49. As was done in the Phase I analysis, bar graphs were plotted showing the relative differences between CODAR, NOAA buoy, and Waverider parameters. Comparisons of individual sensor pairs are detailed below.

CODAR versus NOAA directional buoy

50. Data from the NOAA directional buoy were considered the standard by which CODAR data would be evaluated. There were a total of 549 coincident CODAR and buoy values available for comparison. Figure 20 shows the scatterplots and regression statistics for the 549 data points. The statistics indicate a moderate degree of correlation in significant wave height and little or no correlation in peak period and dominant direction. Mean significant heights from both gages differ by 0.2 ft (0.05 m) or less than 5 percent (Table 5). Differences in mean peak period and dominant direction are larger, 1.3 sec and 24 deg, respectively. Figure 21a shows that the significant height criteria established for acceptable agreement between the two instruments was achieved 26 percent of the time, an improvement over the Phase I results. Dashed lines encompass predetermined performance criteria with percent of data meeting the criteria. There is, once again, a bias toward higher buoy heights (positive x-axis), although not as drastic as that observed in Phase I. This bias may be the result of comparing an area average to a point source. The peak spectral period plot (Figure 21b) indicates that 35 percent of the time the peak periods were within the 1.0-sec acceptance interval, a small improvement over the Phase I results. The bias here is toward longer CODAR periods, a feature also observed in Phase I. Similar also is the large percentage (15 percent) of time when CODAR peak periods are more than 4.5 sec longer than the buoy periods. The dominant direction plot (Figure 21c) shows that the acceptance criterion of 10 deg was met only 15 percent of the time, the same percentage found in Phase I. In fact, the Phase I and II direction bar graphs (Figures 15c and 21c) look remarkably alike, each showing a large percentage (45 percent) of data exceeding a 45-deg difference.

Table 5

Phase II CODAR and NOAA Buoy Statistics*

	Significant Height, m		Peak Period, sec		Dominant Direction, deg		Average Period, sec		Average Direction, deg	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
					All Data					
CODAR	1.01	0.55	9.59	2.32	53	51	7.43	1.02	60	59
NOAA	1.06	0.49	8.30	2.87	77	75	6.82	1.01	83	81
					$H_{mo} < 1$ m					
CODAR	0.68	0.27	9.61	2.22	67	65	7.49	1.01	72	70
NOAA	0.71	0.14	8.73	3.01	88	86	7.02	0.94	95	93
					1 m $< H_{mo} <$ 2 m					
CODAR	1.30	0.47	9.57	2.42	38	36	7.36	1.04	50	49
NOAA	1.35	0.26	7.74	2.60	64	63	6.54	0.95	69	67
					$H_{mo} > 2$ m					
CODAR	2.09	0.44	9.58	2.50	23	21	7.39	0.99	25	24
NOAA	2.33	0.33	8.10	2.61	43	41	6.78	1.38	33	31

* Number of observations = 549.

Table 6

Phase II CODAR and Waverider #650 Statistics*

	Significant Wave Height, m		Peak Period, sec		Average Period, sec	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
			All Data			
CODAR	1.06	0.60	9.54	2.24	7.42	0.94
Waverider #650	1.07	0.53	8.58	3.35	6.89	0.86
			$H_{mo} < 1$ m			
CODAR	0.68	0.25	9.54	2.06	7.52	0.94
Waverider #650	0.70	0.16	8.76	3.14	7.07	0.81
			1 m $< H_{mo} <$ 2 m			
CODAR	1.41	0.53	9.50	2.44	7.30	0.95
Waverider #650	1.39	0.28	8.32	3.46	6.68	0.89
			$H_{mo} > 2$ m			
CODAR	2.12	0.55	9.68	2.51	7.24	0.80
Waverider #650	2.32	0.29	8.52	4.13	6.53	0.67

* Number of observations = 778.

Table 7

Phase II CODAR and Waverider #660 Statistics*

	Significant Wave Height, m		Peak Period, sec		Average Period, sec	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
			All Data			
CODAR	0.91	0.44	9.22	1.80	7.31	0.82
Waverider #660	0.99	0.49	8.09	2.24	6.85	0.73
			H_{mo} < 1 m			
CODAR	0.71	0.28	9.30	2.09	7.04	0.71
Waverider #660	0.72	0.14	8.30	1.77	7.13	0.69
			1 m < H_{mo} < 2 m			
CODAR	1.21	0.39	9.09	2.09	7.04	0.71
Waverider #660	1.33	0.29	7.37	2.07	6.32	0.48
			H_{mo} > 2 m			
CODAR	1.77	0.49	8.97	2.40	7.15	1.03
Waverider #660	2.45	0.34	9.54	5.23	6.34	0.25

* Number of observations = 303.

Table 8

Phase II NOAA Buoy and Waverider #650 Statistics*

	Significant Wave Height, m		Peak Period, sec		Average Period, sec	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
			All Data			
NOAA Buoy	1.15	0.58	8.56	2.78	6.93	1.04
Waverider #650	1.08	0.52	8.67	3.14	6.97	0.93
			H_{mo} < 1 m			
NOAA Buoy	0.69	0.14	8.80	2.94	7.12	0.94
Waverider #650	0.70	0.20	9.03	3.19	7.20	0.79
			1 m < H_{mo} < 2 m			
NOAA Buoy	1.38	0.27	8.31	2.62	6.75	1.09
Waverider #650	1.28	0.30	8.34	3.16	6.79	1.02
			H_{mo} > 2 m			
NOAA Buoy	2.42	0.45	8.39	2.53	6.78	1.18
Waverider #650	2.09	0.45	8.25	2.51	6.63	0.95

* Number of observations = 503.

Table 9

Phase II NOAA Buoy and Waverider #660 Statistics*

	Significant Wave Height, m		Peak Period, sec		Average Period, sec	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
			All Data			
NOAA Buoy	0.89	0.41	8.32	2.06	7.01	0.90
Waverider #660	0.86	0.37	8.15	1.62	7.03	0.83
			H_{mo} < 1 m			
NOAA Buoy	0.71	0.14	8.53	2.14	7.24	0.85
Waverider #660	0.71	0.16	8.36	1.57	7.24	0.78
			1 m < H_{mo} < 2 m			
NOAA Buoy	1.28	0.24	7.90	1.61	6.32	0.59
Waverider #660	1.21	0.28	7.72	1.63	6.43	0.64
			H_{mo} > 2 m			
NOAA Buoy	2.29	0.22	6.39	0.43	5.94	0.24
Waverider #660	2.02	0.25	6.27	0.46	5.96	0.17

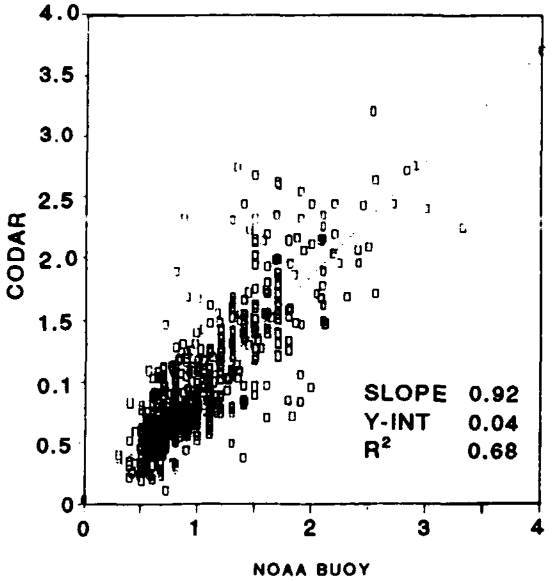
* Number of observations = 169.

Table 10

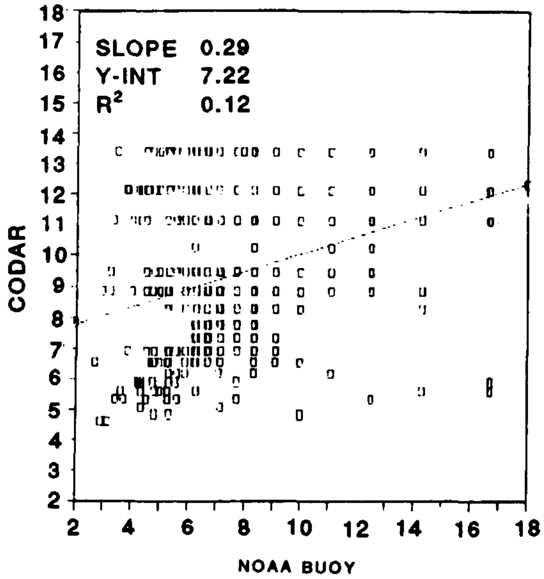
Phase II Waverider #660 and Waverider #650 Statistics*

	Significant Wave Height, m		Peak Period, sec		Average Period, sec	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
			All Data			
Waverider #660	1.05	0.61	8.15	1.64	4.96	0.77
Waverider #650	1.03	0.62	8.40	1.94	4.88	0.76
			H_{mo} < 1 m			
Waverider #660	0.75	0.18	8.27	1.58	4.99	0.84
Waverider #650	0.72	0.15	8.55	1.94	4.88	0.82
			1 m < H_{mo} < 2 m			
Waverider #660	1.36	0.32	7.99	1.75	4.88	0.61
Waverider #650	1.29	0.26	8.18	1.89	4.85	0.65
			H_{mo} > 2 m			
Waverider #660	2.69	0.61	7.71	1.65	4.95	0.66
Waverider #650	2.79	0.57	7.78	1.88	4.62	0.52

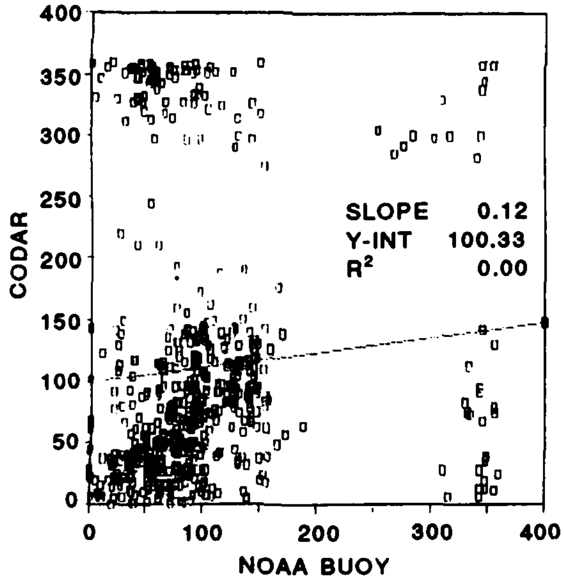
* Number of observations = 359.



a. Significant wave height, m

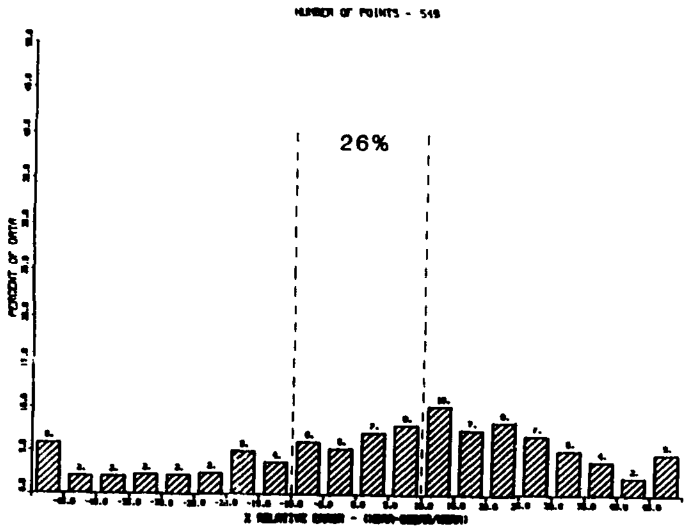


b. Peak period, sec



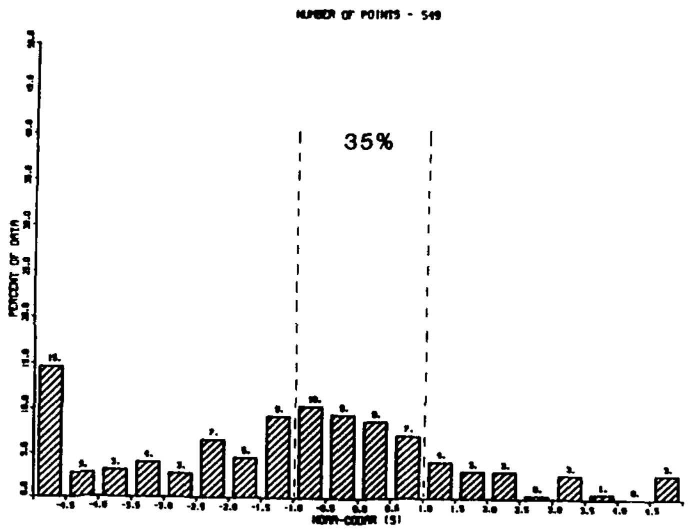
c. Dominant direction, deg T

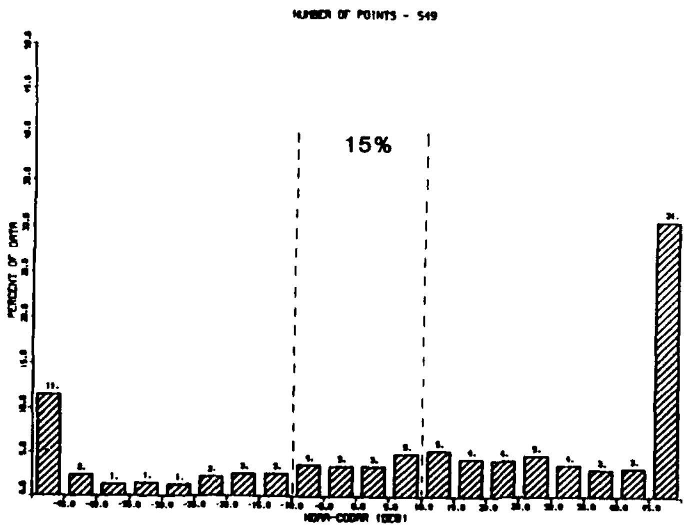
Figure 20. Phase II scatterplot of 549 CODAR/NOAA buoy data



a. Significant wave height

b. Peak spectral period





c. Dominant direction

Figure 21. Bar graph showing differences in CODAR/NOAA buoy data

CODAR versus Waverider #650

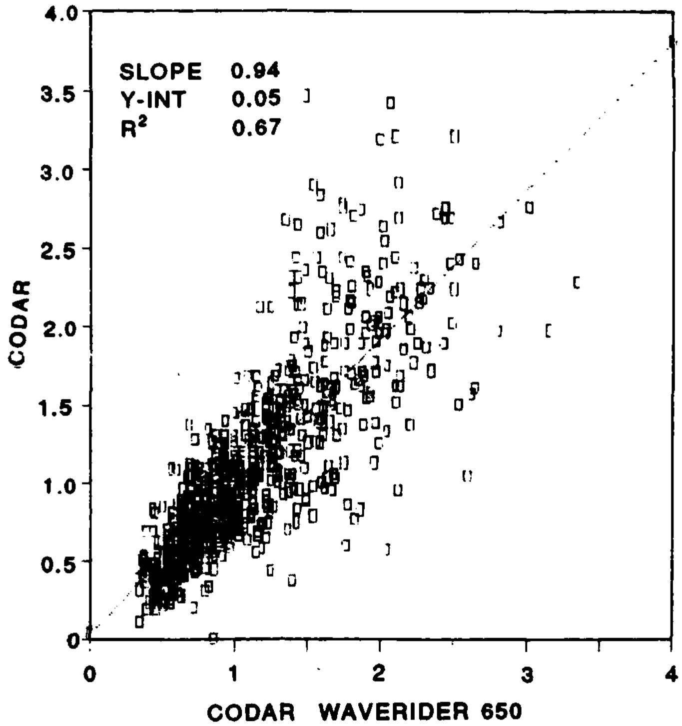
51. The Waverider #650 buoy was located approximately 13 miles (21 km) northwest of the NOAA buoy in water 70 ft (21 m) deep. This buoy was placed slightly beyond the CODAR coverage area to avoid the large amount of trawler traffic in the vicinity. Figure 22 shows the scatterplots and regression statistics for 778 coincident data points. The correlation in significant height is similar to that observed for the CODAR/NOAA buoy case. Peak periods exhibit little correlation. Difference in mean significant height and peak period between CODAR and both Waveriders #650 and #660 are similar to those between CODAR and the NOAA buoy (Tables 6 and 7). Figure 23 shows the bar graphs associated with a CODAR/Waverider #650 comparison using the same criteria as those used for CODAR/NOAA buoy comparisons. Figure 23a shows that significant wave height differences were within the established guidelines 30 percent of the time, a figure in close agreement with the CODAR/NOAA buoy comparisons. The peak spectral period graph (Figure 23b) indicates an acceptance level of 41 percent, again very similar to CODAR/NOAA buoy data. This data set shows the same bias toward higher buoy wave heights and longer CODAR peak periods. No direction is available from the Waveriders.

CODAR versus Waverider #660

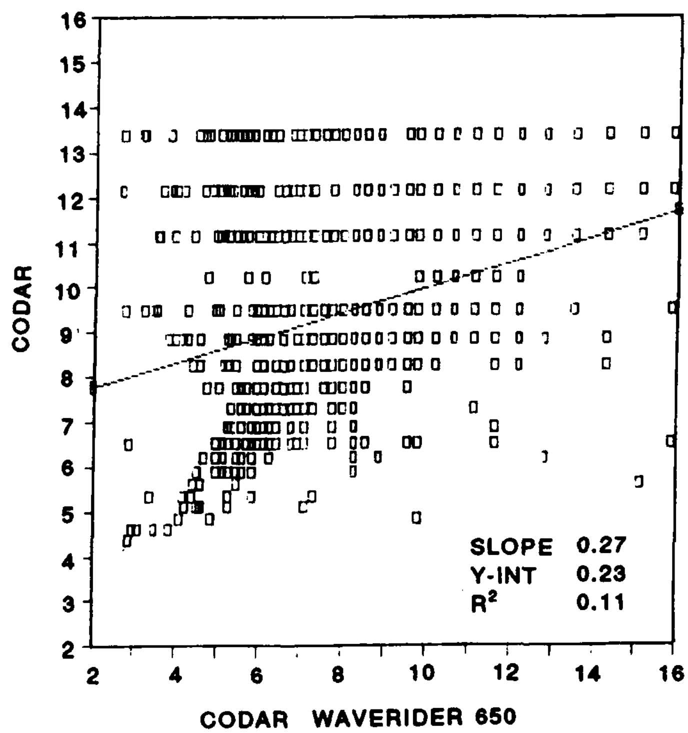
52. The Waverider #660 was located approximately 8 miles (13 km) southwest of the NOAA buoy and 17 miles (27 km) south-southeast of Waverider #650 in about 70 ft (21 m) of water. This buoy was torn from its mooring early in the experiment, limiting available data to 7 weeks. Figure 24 (a, b) shows the scatterplots and regression statistics for 303 coincident values. The correlation in significant height is again similar to previous CODAR/buoy cases. Peak period continues to show very little correlation. Figure 25 shows the bar graphs for significant wave height and peak spectral period. Using the same criteria as before, Figure 25a shows that significant wave heights were within the acceptance levels only 19 percent of the time with a bias toward higher Waverider values. Peak spectral period data (Figure 25b) shows a somewhat higher 48 percent acceptance with a bias toward longer CODAR periods.

NOAA Buoy versus Waverider #650

53. To independently check buoy performance and to establish perspective on what constitutes successful conformance with the accuracy criteria, the same analysis was carried out on a buoy-versus-buoy basis.

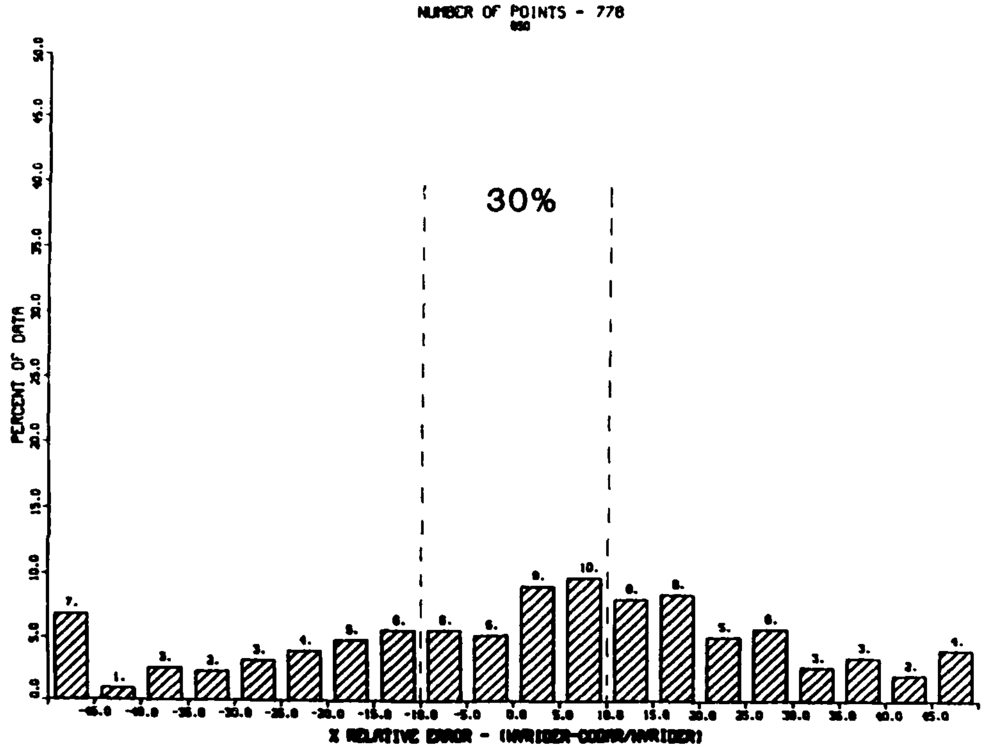


a. Significant wave height, m

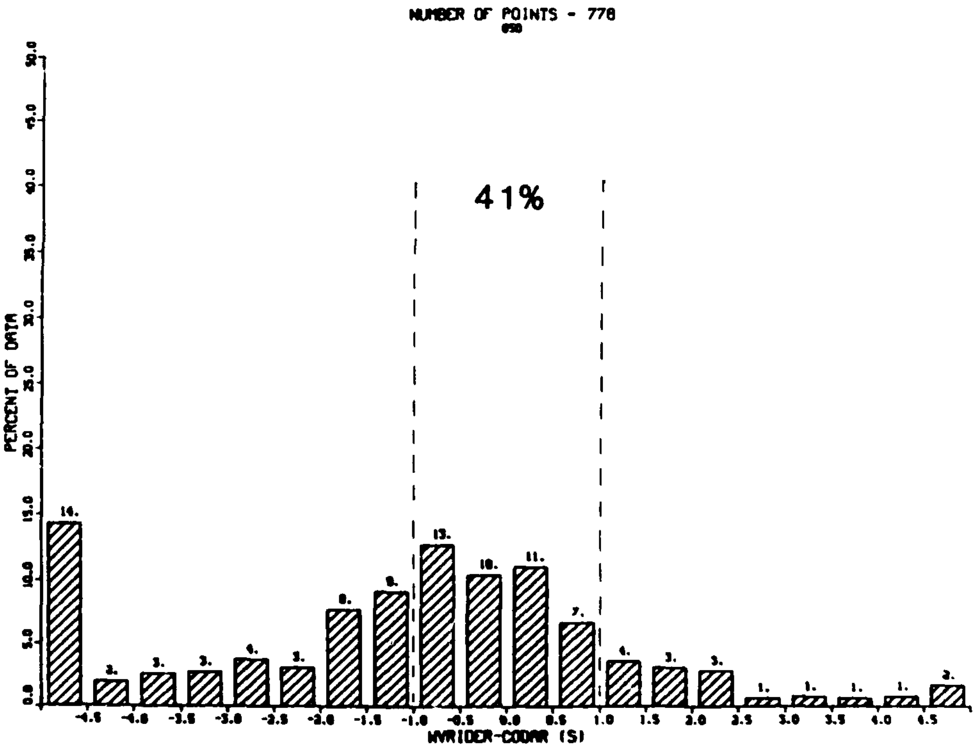


b. Peak spectral period, sec

Figure 22. Phase II scatterplot of 778 CODAR/Waverider #650 data points

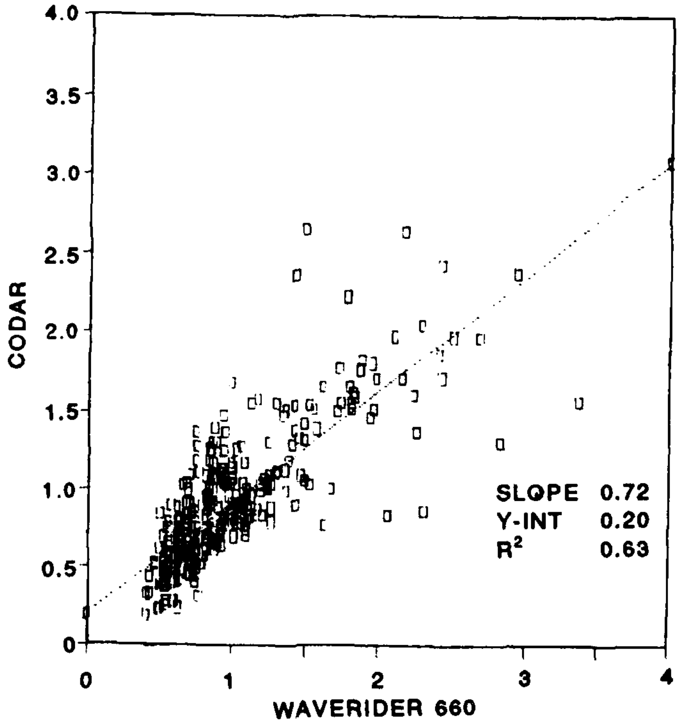


a. Significant height

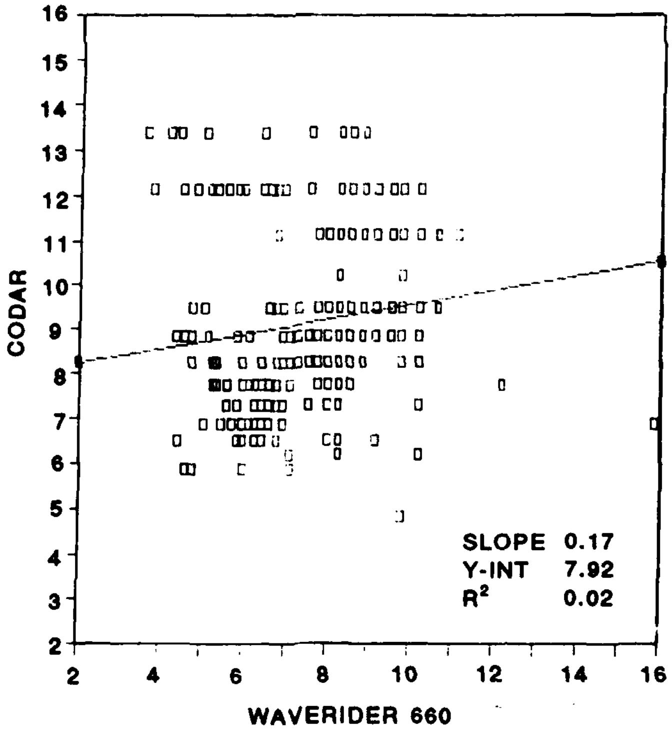


b. Peak spectral period

Figure 23. Bar graph showing differences
in CODAR/Waverider #650 data

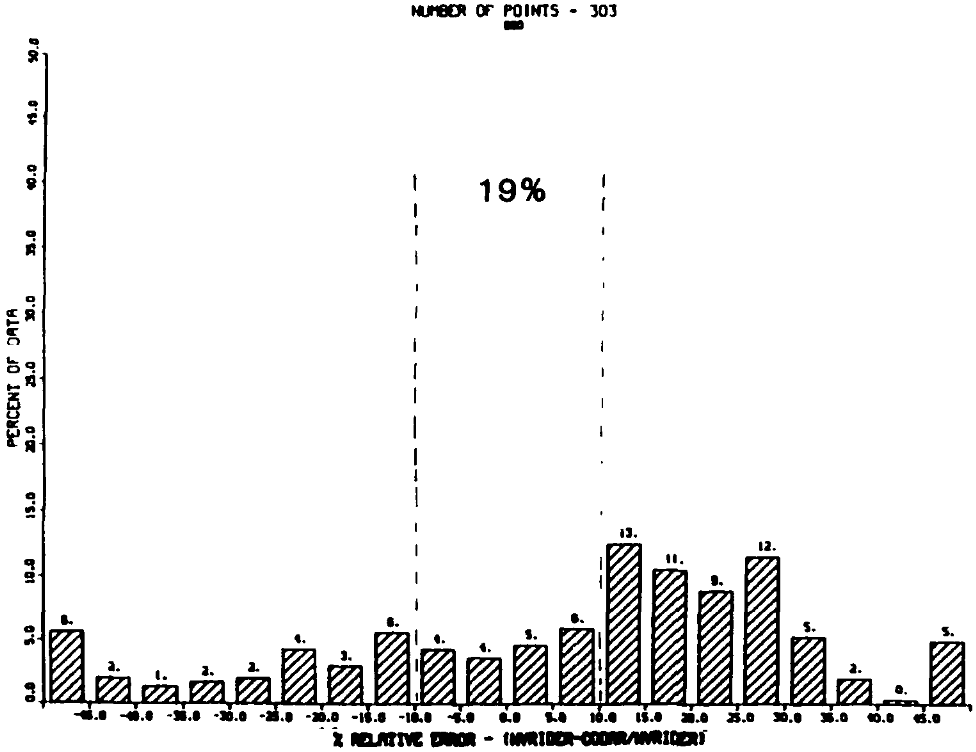


a. Significant wave height, m

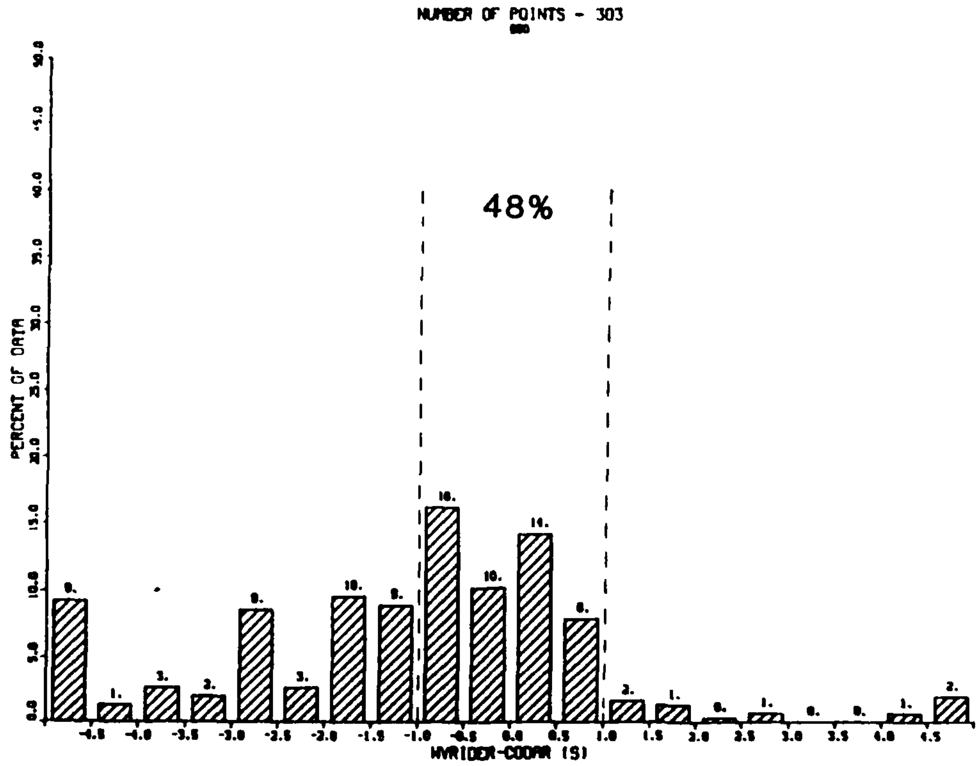


b. Peak spectral period, sec

Figure 24. Phase II scatterplot of 303 CODAR/Waverider #660 data points



a. Significant wave height



b. Peak spectral period

Figure 25. Bar graph showing differences in CODAR/Waverider #660 data

54. Figure 26 shows the scatterplots and regression statistics for the 503 coincident NOAA buoy and Waverider #650 data points. Correlation between significant wave heights is considerably better than that exhibited in the CODAR comparisons. Peak period correlation shows some improvement. Figure 27a indicates that, given the same criteria used to judge CODAR, significant wave heights from the two buoys were within the given interval 54 percent of the time. This is twice the percent acceptance value for CODAR versus the NOAA buoy. Also of note is the difference in the overall shape of the distribution in Figure 27a as opposed to Figures 23a and 25a. Figure 27a displays a more nearly normal distribution with a slight bias toward larger NOAA waves. The peak spectral period graph (Figure 27b) shows that the two periods agreed to within 1.0 sec 70 percent of the time.

NOAA Buoy versus Waverider #660

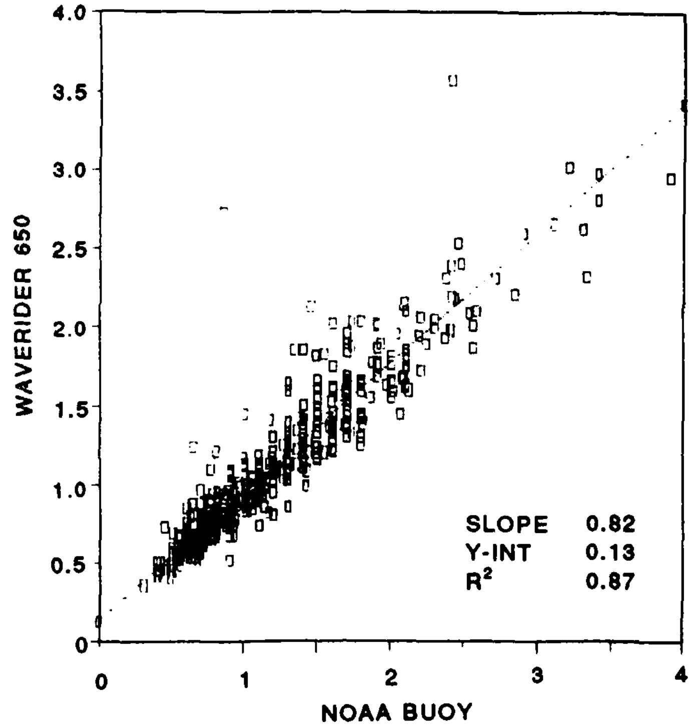
55. Figure 28 shows the scatterplots and regression statistics for 169 coincident values. Significant wave heights are well correlated for this pair, while peak periods show little correlation. Figure 29 represents the differences between NOAA buoy measurements and Waverider #660 measurements. Significant wave heights are within the 10-percent interval 56 percent of the time, which agrees well with the corresponding value for the NOAA buoy/Waverider #650 data. Peak spectral periods are within 1.0 sec of each other 74 percent of the time.

Waverider #650 versus Waverider #660

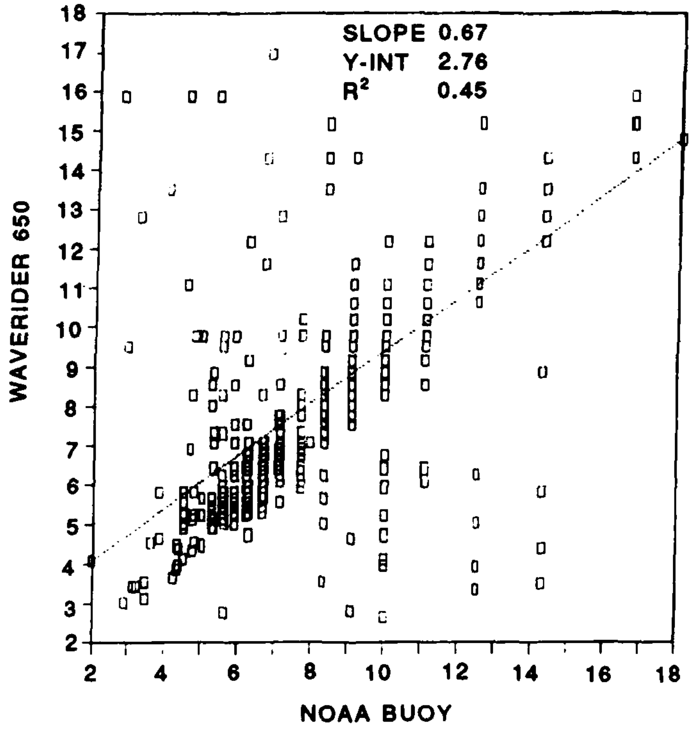
56. Scatterplots and regression statistics for 359 coincident Waverider #650/Waverider #660 data points are shown in Figure 30. The plots and statistics are similar to other buoy/buoy comparisons, showing a relatively high degree of correlation between significant wave heights and little correlation between peak periods. Significant wave height and peak spectral period differences for the two Waveriders are shown in Figure 31. Wave heights are within 10 percent of one another 54 percent of the time, with a bias toward higher waves at #660. Peak periods are within specified limits 74 percent of the time. These percentages agree well with all previous buoy-versus-buoy comparisons.

Shallow-Water Measurements

57. Data from the linear array directional wave gage were limited due

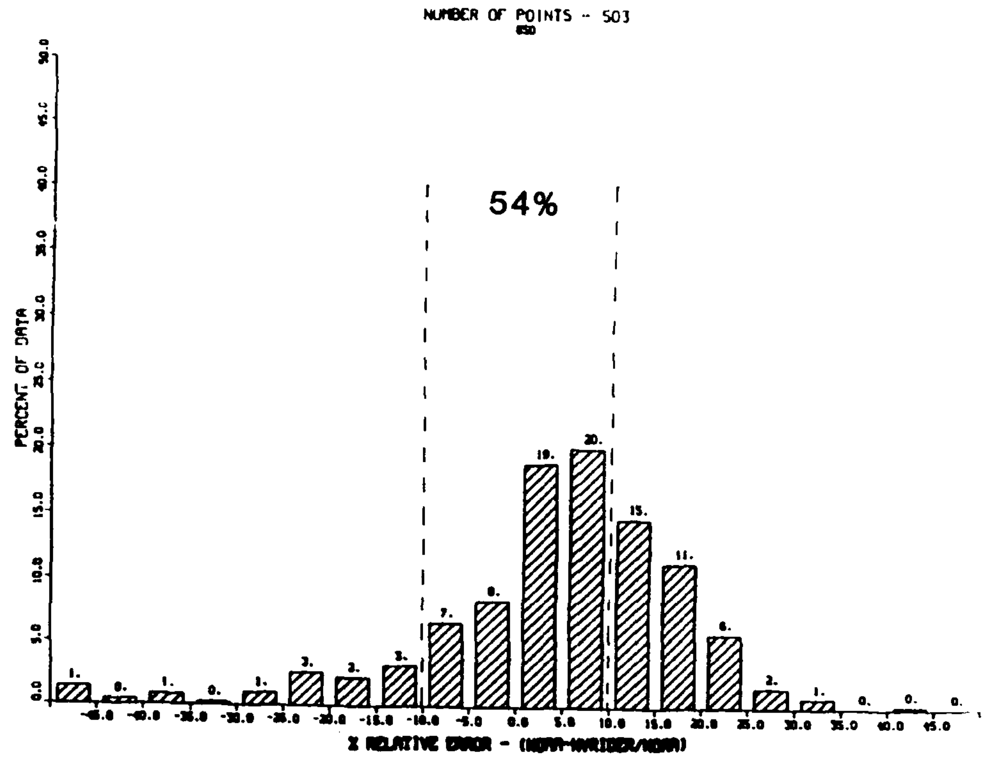


a. Significant wave height, m

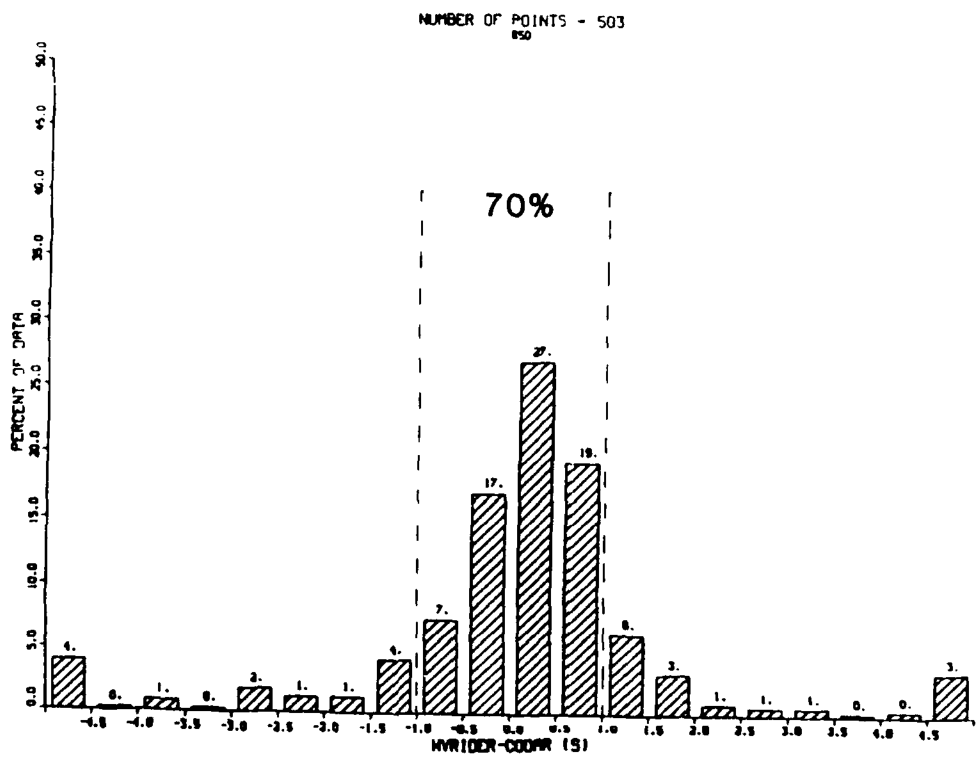


b. Peak spectral period, sec

Figure 26. Phase II scatterplot of 503 NOAA buoy/Waverider #650 data points

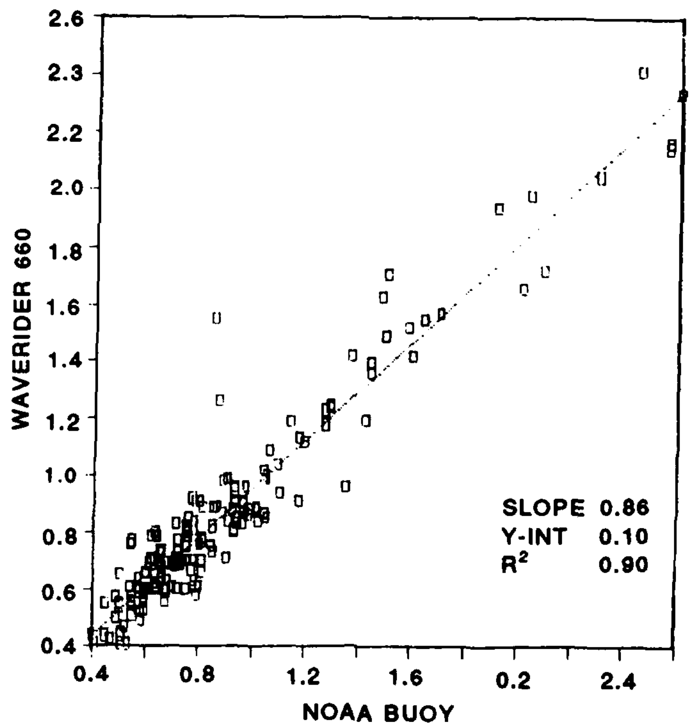


a. Significant wave height

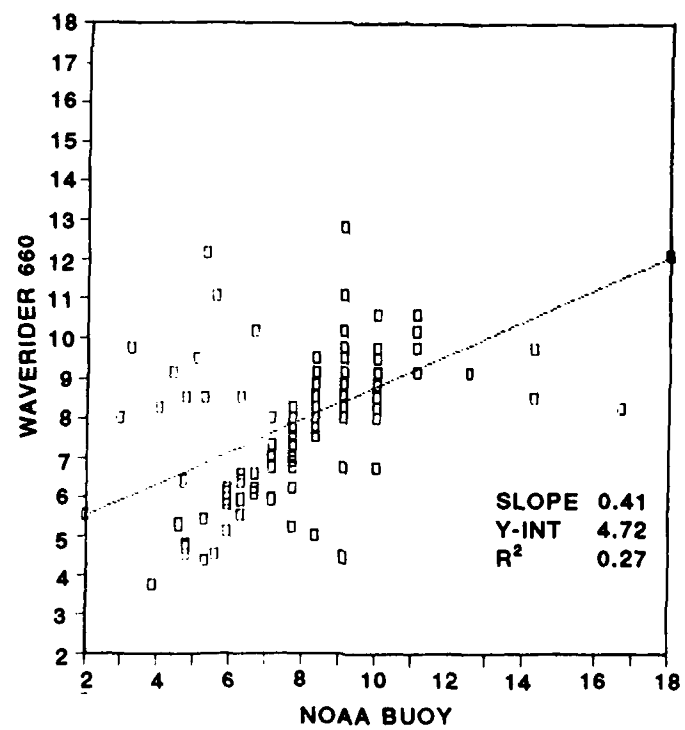


b. Peak spectral period

Figure 27. Bar graph showing differences in NOAA buoy/Waverider #650 data

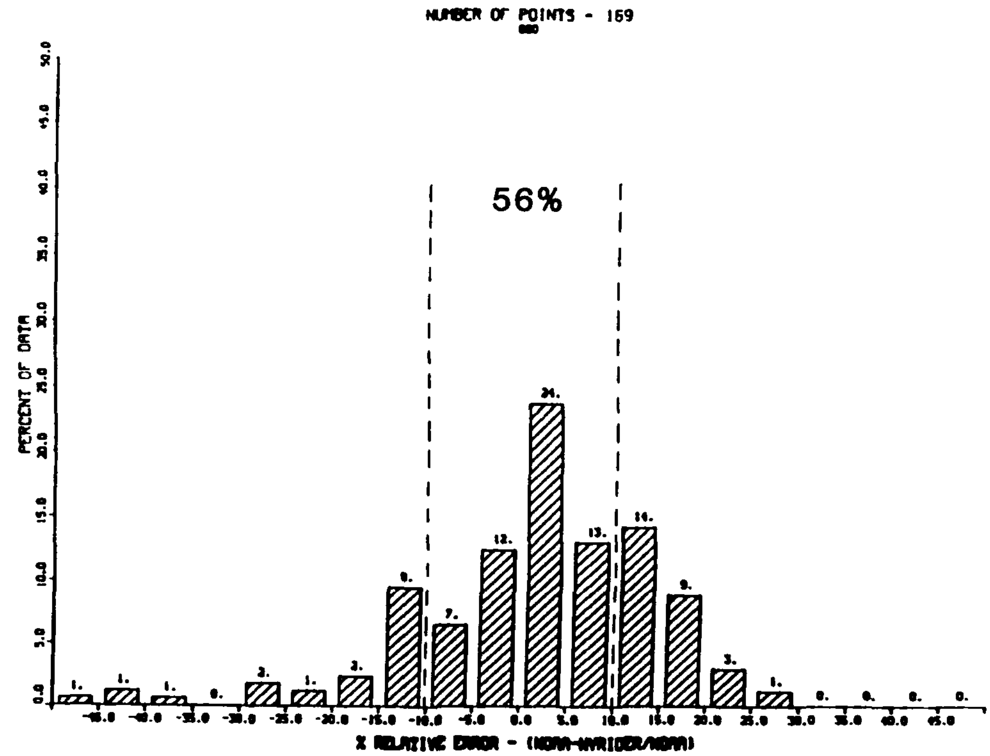


a. Significant wave height, m

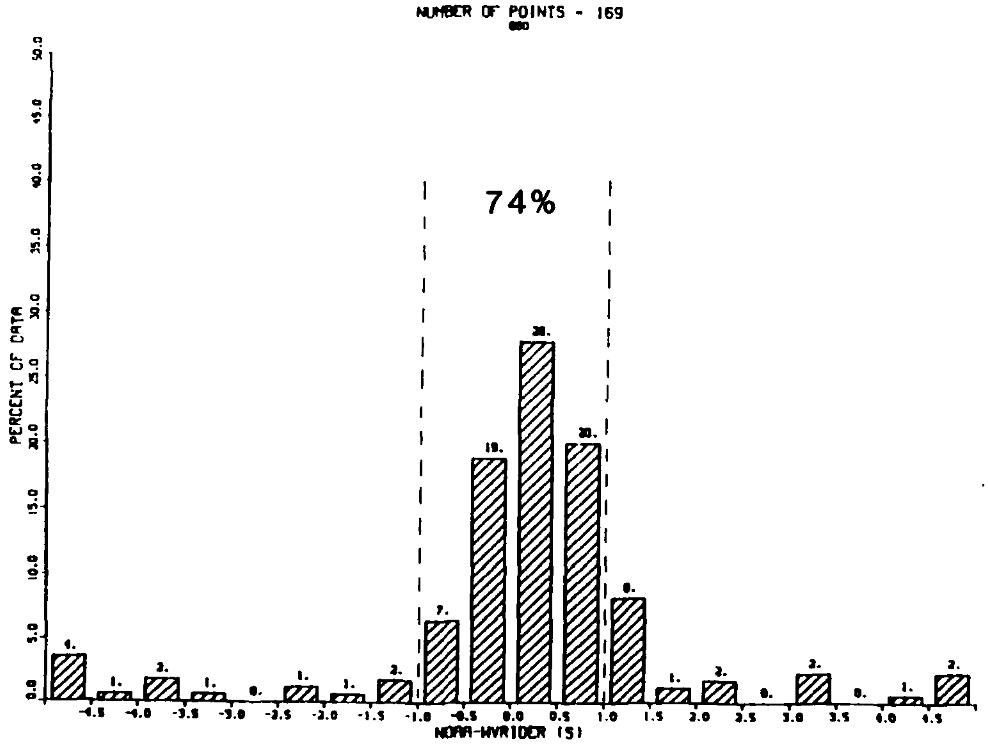


b. Peak spectral period, sec

Figure 28. Phase II scatterplot of 169 NOAA buoy/Waverider #660 data points

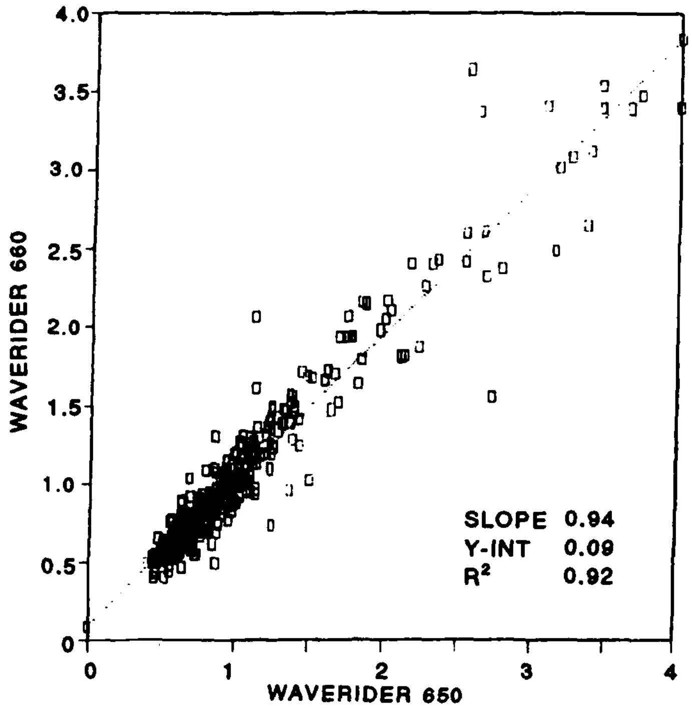


a. Significant wave height

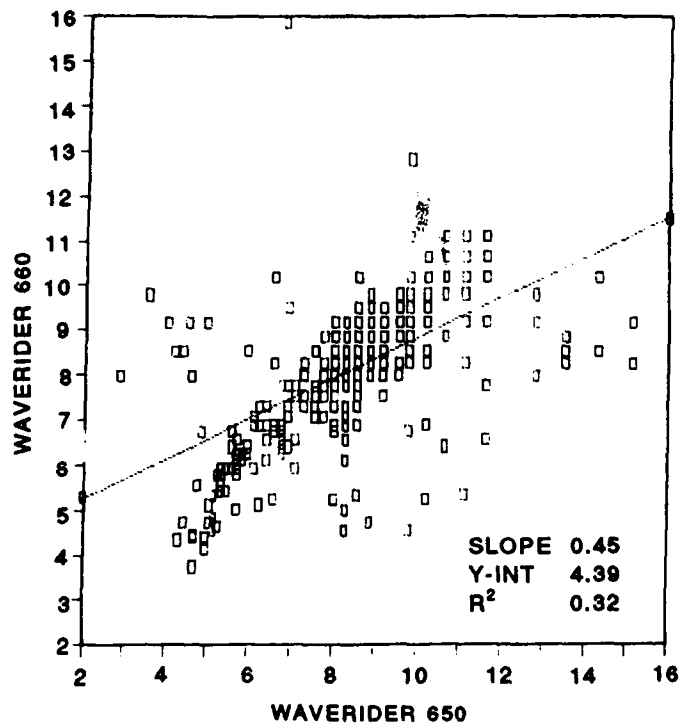


b. Peak spectral period

Figure 29. Bar graph showing differences in NOAA buoy/Waverider #660 data

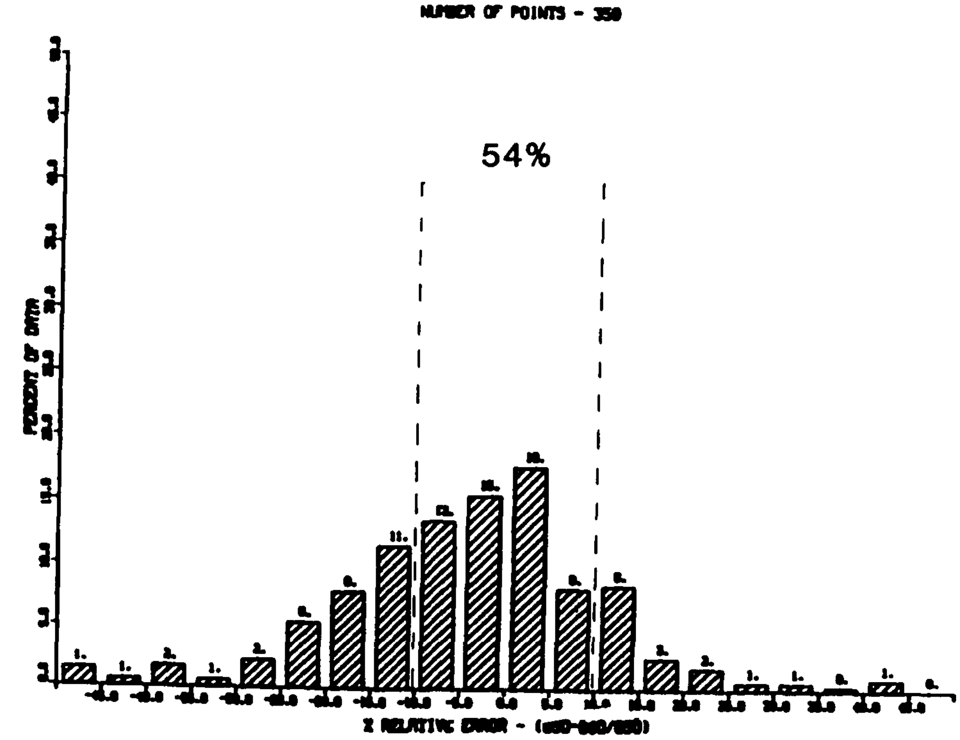


a. Significant wave height, m

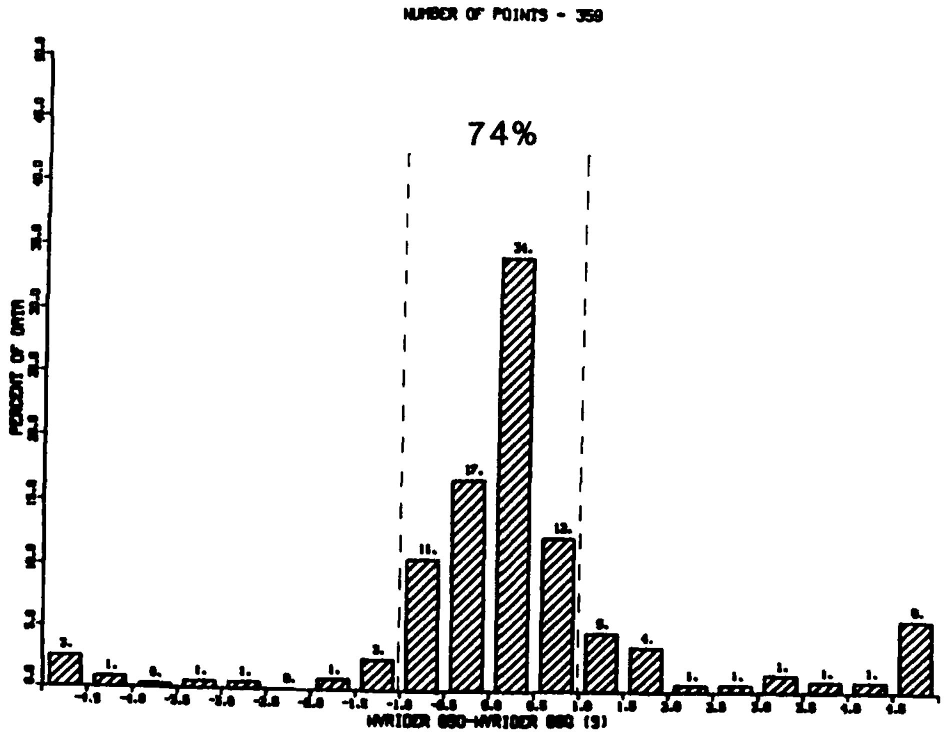


b. Peak spectral period, m

Figure 30. Phase II scatterplot of 359 Waverider #650/Waverider #660 data points



a. Significant wave height



b. Peak spectral period

Figure 31. Bar graph showing differences in Waverider #650/Waverider #660 data

to computational requirements. Nearshore wave direction data were collected at various times on 8 separate days and, using the procedure outlined in Appendix C, the direction at a water depth of 90 ft (27 m) was determined. This direction was then compared with the directions measured by CODAR and the NOAA buoy. The transformed linear array wave direction was within 20 deg of the NOAA buoy direction 71 percent of the time and within 20 deg of the CODAR direction 14 percent of the time. Table 11 provides a comparison of NOAA buoy, CODAR, and converted linear array data.

Table 11

Comparison of NOAA Buoy, CODAR, and Converted Linear Array Data

		Height, m			Period, sec			Direction, deg		
Date	Time	N*	C	LA	N	C	LA	N	C	LA
9/20	1900	1.6	1.5	1.4	8.3	7.8	8.9	55	28	68
9/20	2200	1.6	1.5	1.4	8.3	6.9	8.2	--	29	77
9/23	0400	0.8	0.6	0.6	9.1	8.9	9.7	60	115	72
9/23	0700	0.8	0.6	0.7	10.0	12.2	9.7	81	16	70
10/2	1600	0.9	1.3	0.7	9.1	8.9	9.7	99	46	81
10/2	1900	0.9	1.4	0.7	9.1	8.9	8.9	99	141	79
10/4	0700	2.5	2.4	1.8	7.1	8.9	7.0	342	13	60
10/4	1000	2.6	2.6	1.5	6.7	6.9	8.2	359	25	40
12/24	1600	0.9	0.7	0.8	9.1	8.3	10.7	95	137	82
12/24	1900	0.9	0.7	0.8	8.3	7.8	10.7	87	141	82
12/25	1000	0.9	0.8	0.7	12.5	13.4	13.6	79	125	74
12/25	1300	1.0	0.9	0.8	12.5	9.5	13.6	73	81	74
1/13	2200	--	1.9	1.8	10.0	8.9	5.5	94	333	18
1/14	0100	3.0	2.4	2.0	6.7	7.3	6.6	356	12	20
1/14	0400	2.9	2.8	2.5	7.1	13.4	7.0	9	346	24

* N = NOAA buoy, C = CODAR, LA = linear array.

Discussion

58. Many of the problems encountered in Phase I of the CRSDP were eliminated by conducting Phase II at the FRF. There were several minor difficulties and disappointments encountered, including a 7-week period when the NOAA buoy was nonfunctional, a 1-week period during which CODAR was disabled, the early loss of Waverider #660, and the inability to make the planned SCR overflight. None of these, however, seriously jeopardized the success of Phase II.

59. A serious problem encountered was the known inability of CODAR, operating at 25.4 MHz, to measure waves higher than 8 ft (2.5 m). This radar frequency-dependent limitation was to be overcome by the implementation and utilization of a lower radar frequency (6.8 MHz) that would be automatically activated when wave conditions exceeded a preset threshold. This dual-frequency capability had been installed on the system prior to the Phase II data collection effort but was untested. Unfortunately, an incompatibility between the 6.8 MHz frequency and receiver hardware was discovered and could not be easily resolved. Thus, the 6.8-MHz frequency could not be successfully brought on line. As a result, there were several instances of lost data when the significant wave height exceeded 8 ft (2.5 m) (Figure 32). This inability to measure large waves is a major detriment, particularly during local storm events when waves of interest often exceed these limits. These lost data can provide at least one possible reason for the differences observed in the mean

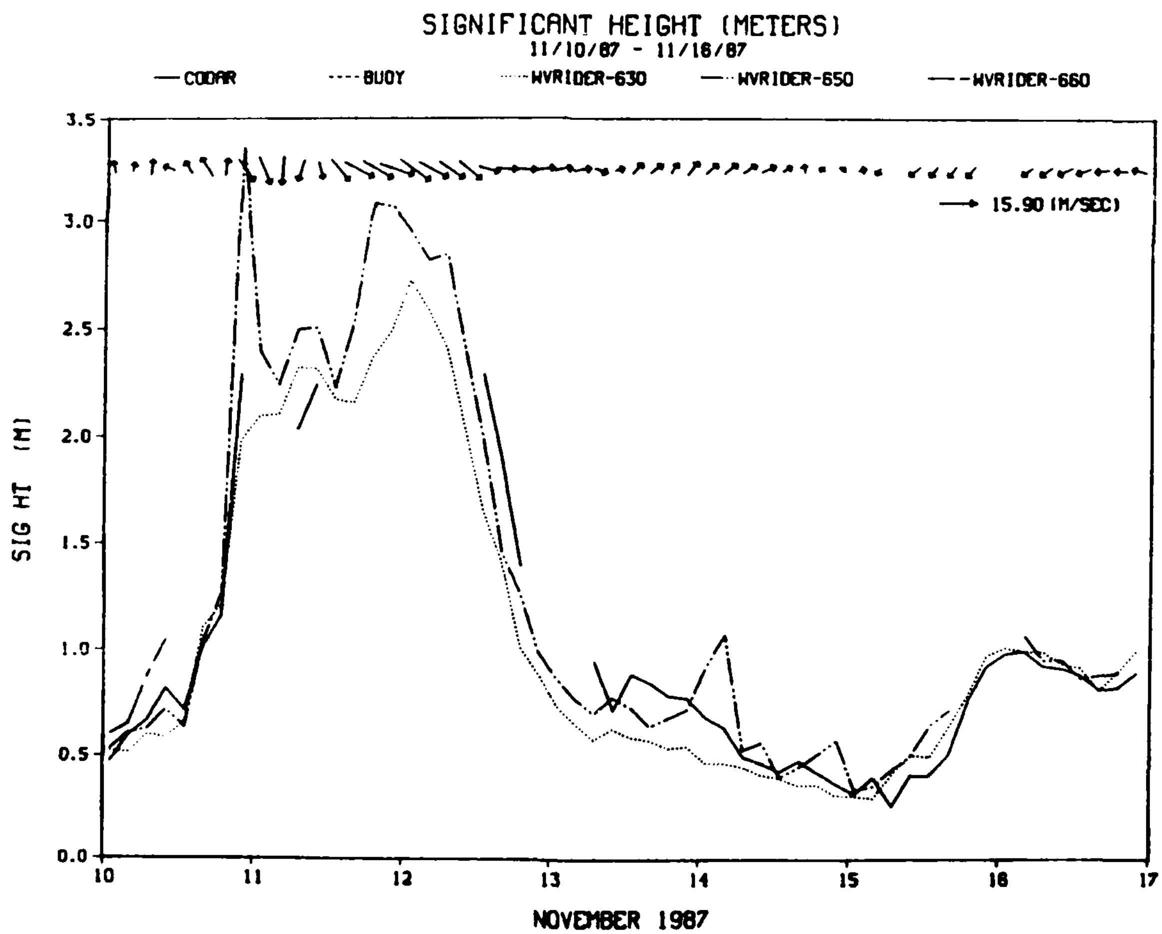


Figure 32. Time series plot showing lack of CODAR data at significant wave heights exceeding 8 ft (2.5 m)

values (Tables 4-7) when significant heights exceeded 2 m. In addition to large waves, storms also produce locally strong surface currents in response to the wind. The currents, as previously discussed, further inhibit CODAR's capability. It was expected that the 6.8-MHz frequency would be able to operate in higher currents, but this capability could not be demonstrated.

60. In terms of the stated objectives, Phase II of the CRSDP was a success. The goal was to conduct a test that would, at a minimum, determine whether or not the CODAR system could provide operational wave parameters under optimum conditions; i.e. no persistent, strong surface currents; a minimum of ship traffic; no offshore islands; and reasonably straight, parallel depth contours. Proven wave measuring buoys were placed at stategic locations in an effort to provide quality comparative data. The result was a highly successful data collection effort that yielded approximately 75 sensor-weeks of data.

61. As detailed in the analysis section, the criteria established prior to Phase I for acceptable differences between CODAR and NOAA buoy data were met only a small fraction of time for significant height and peak period. Differences for peak direction were large and quite variable, and there was little evidence of overall consistency between the two data sources. Table 12 shows the percent of observations that fall within the established criteria for each sensor pair. The numbers indicate that CODAR is within the limits roughly 50 percent as often as traditional instruments.

Table 12

Percent of Observations Within Acceptance Criteria for Each Sensor Pair, Phase II

Sensor Pair	Significant Wave Height % Acceptance	Peak Period % Acceptance	Dominant Direction % Acceptance
CODAR/NOAA Buoy	26	35	15
CODAR/Waverider #650	30	41	--
CODAR/Waverider #660	19	48	--
Waverider #650/NOAA Buoy	54	70	--
Waverider #660/NOAA Buoy	56	74	--
Waverider #650/ Waverider #660	54	74	--

62. Differences between CODAR and NOAA buoy estimates of wave direction were explored in more detail. In cases where the two estimates were nearly the same, the spectra tended to be reasonably well-formed with a clearly dominant peak. An example is provided in Figure 33, where the NOAA peak direction of 83.5 deg is close to the CODAR direction of 83 deg. In cases where there are large differences in direction, many result from the fact that a number of CODAR spectra exhibit an inexplicably large change in direction in the vicinity of the spectral peak (Figure 34). In addition, wind data from the NOAA buoy were examined along with the NOAA and CODAR wave estimates. When the two wave direction estimates compared poorly, the wind direction usually had a significant alongshore component. However, alongshore winds did not always coincide with poor agreement between CODAR and the NOAA buoy.

63. The CODAR/NOAA buoy comparisons for significant height in Phase II are improved over those in Phase I (Figures 15a and 21a), but they are still far less than normally accepted. The comparisons for peak period and direction are about the same in both Phases I and II. The improvement in height is expected, since the CODAR and buoy measurement locations overlapped in Phase II and not in Phase I. The consistency in period comparisons is also reasonable, since wave period is not expected to change greatly over short propagation distances and initial shoaling. The lack of improvement in peak direction comparisons in Phase II is difficult to explain other than by noting that the two directional estimates show little relationship to each other.

64. It was expected from the beginning of CRSDP that not all observations from a large data comparison set would meet the criteria established for success. Perspective on what constitutes a reasonable level of success is provided by the various buoy-versus-buoy comparisons. These comparisons clearly show that the CODAR estimates are not as consistent as the buoy estimates.

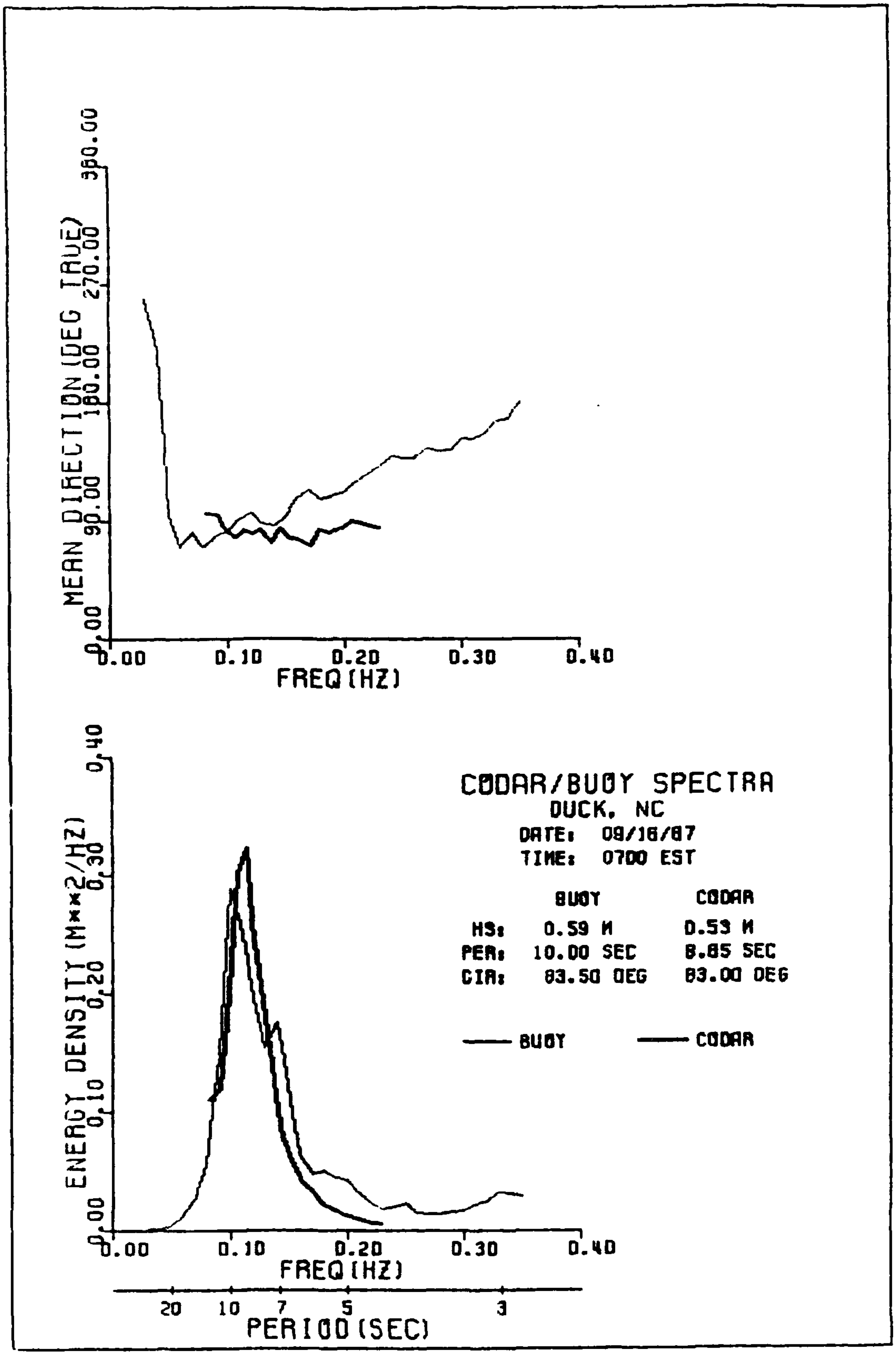


Figure 33. Plot of CODAR and NOAA buoy spectra with sharp, well-defined peaks

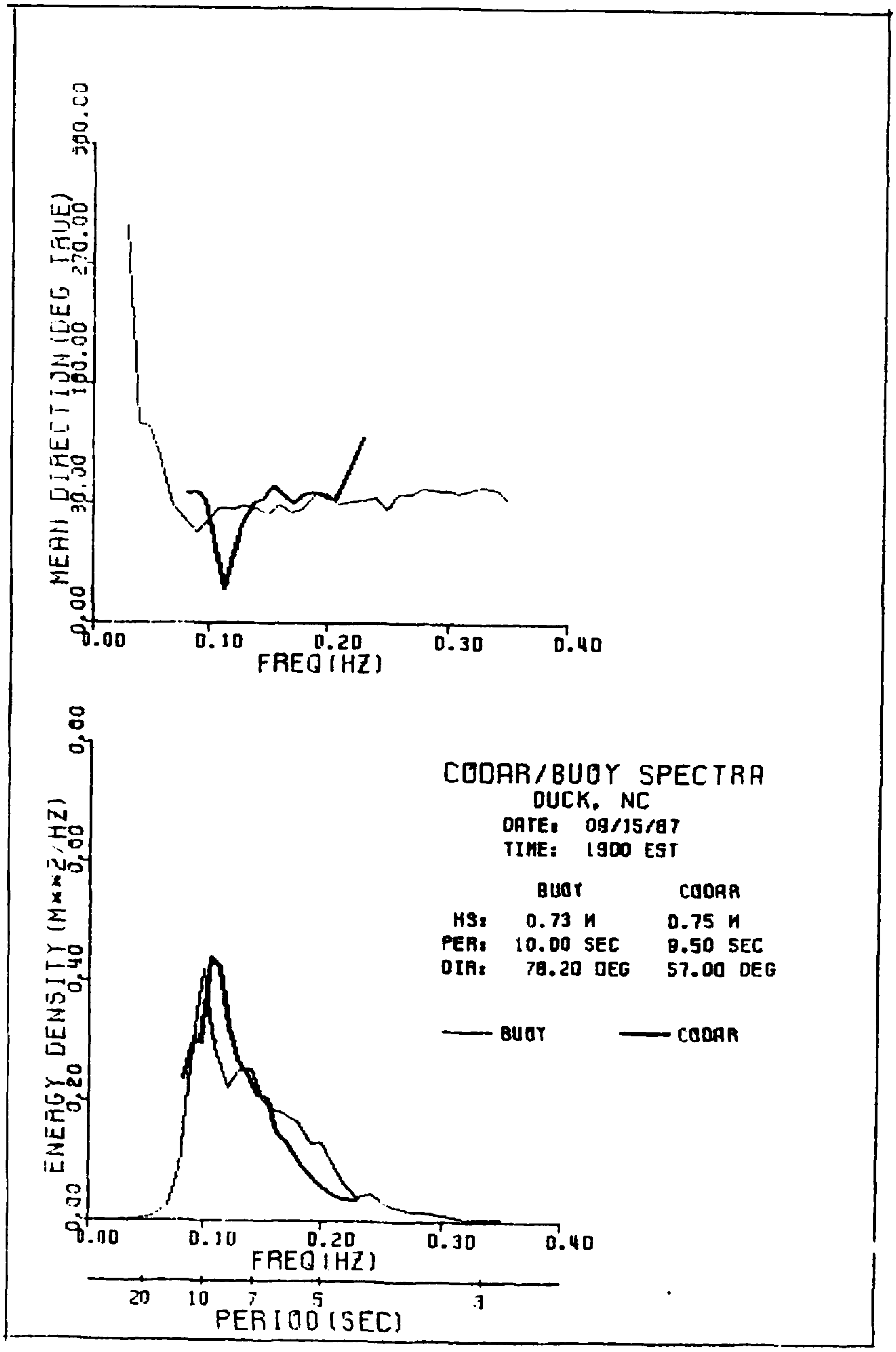


Figure 34. Plot of CODAR and NOAA buoy spectra showing inexplicable deviation in CODAR-measured mean wave direction

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

65. The CRSDP has demonstrated in two field experiments that the CODAR high-frequency radar system can be operated along the coast and provide some information on coastal waves. However, there are some important concerns and limitations on the existing system which seriously limit possibilities for practical use.

66. The CODAR is very different from conventional wave measurement systems. Important features of the CODAR system as compared with conventional wave measurement systems are listed in Table 13. The CODAR features are representative of the particular system used by CERC in the CRSDP program. Some of the limitations of the present system may be reduced or removed in future generation systems. Among these are the limited range of wave height measurement and some of the special site requirements.

67. The CODAR system has some apparent advantages. The entire system is located on land adjacent to the water. Thus it is accessible for servicing. This advantage was demonstrated in Phase II when both CODAR and the NOAA buoy failed within a 2-day period in October 1987. A technician visited the CODAR site as soon as possible and repaired the system within 1 day. The total downtime was 7 days. Required maintenance and changes in the operational schedule of the Coast Guard vessel caused a delay in the service visit of 51 days. This downtime may have been reduced significantly under different circumstances.

68. The broad, annular coverage area is another limitation of CODAR. The point measurement provided by conventional gages is also limited in value, but that limitation is familiar to most coastal engineers and reasonably well understood. From discussions at the working group meetings, the preferred coverage would be a small area on the order of 0.2 to 0.5 mile (0.32 to 0.80 km) square.

69. The most serious limitations with the present CODAR system were as follows:

- a. Inability to measure significant wave heights greater than 8 ft.
- b. Apparent sensitivity to signal loss when wind-generated currents are stronger than about 1.5 knots (0.77 m/sec).

Table 13

Comparison of CODAR and Conventional Wave Gage Features

Item	CODAR	Conventional Offshore Wave Gage
Location	Land	Water; may be components on land
Power supply	120-V AC	Battery or 120-V AC
Shelter	Climate-controlled room	Varies
Serviceability	Access by vehicle Limited commercial support	Access by boat Broader commercial support
Value of hardware	$150 K	$20 to 30 K (nondirectional) $50 to 500 K (directional)
Coverage	Average over annulus	Point
Range of measurement	0.5 to 8.0-ft (0.15 to 2.4 m) wave height	Full range of wave height
Most likely causes of data loss	Currents Ship traffic	Transmission loss Ship-induced damage
Special site requirements	Relatively regular bathymetry No offshore islands No currents above 1.5 knots (0.77 m/sec) Minimal ship traffic Accessibility to beach	Varies with system but typically no serious limitations.

c. Broad annular coverage.

d. Very limiting special site requirements.

e. Erratic estimates of dominant wave direction.

These limitations seriously constrain the range of applications for this CODAR system.

70. The CODAR system software is quite versatile and allows considerable freedom for checking system operation, modifying the data collection scheme, and generating special information and displays. For the computer-literate young engineers and technicians of today, the system is appealing, easy to learn (as demonstrated by US Army Engineer District, Los Angeles personnel), and amenable to customizing to suit individual needs and capabilities.

Recommendations

Wave measurement with high-frequency radar

71. Because of its serious limitations, detailed in the preceding section, the present CODAR system is not recommended for routine wave data collection in the Corps of Engineers. Further development of high frequency radar systems for wave measurement is underway in the US and several other countries. It is conceivable that future generation systems will overcome some of the limitations in the present system. However, it is recommended that any high-frequency radar system considered for routine use in the Corps be scrutinized relative to these limitations.

Future evaluation of coastal sensors

72. The Corps of Engineers has a strong need for improved instrumentation for measuring processes along the coast. This need encompasses not only waves but also currents, sediment transport, bottom elevation, etc. Coastal processes are highly variable and complex, and conducting a field experiment which clearly demonstrates the capabilities of a new device is a challenging task. As a result of the CRSDP experience, several recommendations can be made which, if followed in future sensor evaluation experiments, will significantly improve the chances for a definitive evaluation.

73. Location. The field location should be carefully chosen to minimize the complexity of the processes being measured. Even the simplest field situations are quite complex.

74. Customization. The project should have sufficient resources to customize the experiment to achieve the desired evaluation. Thus the project should include at least several measurement stations with the most accurate, reliable sensors available.

75. Auxiliary support. The field location should also be chosen to take advantage of appropriate auxiliary support if possible. The support may include existing instrumentation in support of other projects. It may also include personnel and equipment such as a shop, vehicles, computer system, etc.

76. Documentation of new sensor. The new sensor to be evaluated should be accompanied by clear and detailed documentation. The documentation should include principles of operation, hardware, and software. This information is essential to interpreting the performance of the sensor and assessing possibilities for improvement.

77. The CRSDP Phase I site was selected primarily because of auxiliary support. The complexity of the site, the lack of control over the primary conventional instrumentation, and the insufficient level of documentation of the system created difficult problems. In Phase II all four of the recommendations were followed, and all four contributed very significantly to its success. The level of documentation of the CODAR system during Phase II, though much improved over Phase I, was still short of the ideal. The FRF location and auxiliary support were major ingredients in Phase II. The unique value of the FRF to the Corps of Engineers and the coastal engineering community was again highlighted during this demonstration program.

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APPENDIX A: PHASE I TIME SERIES PLOTS

Time series of significant wave height, peak spectral period, and dominant wave direction, as measured by CODAR and the NOAA buoy, are plotted in one-half-month time intervals from 1 May to 29 June 1986.

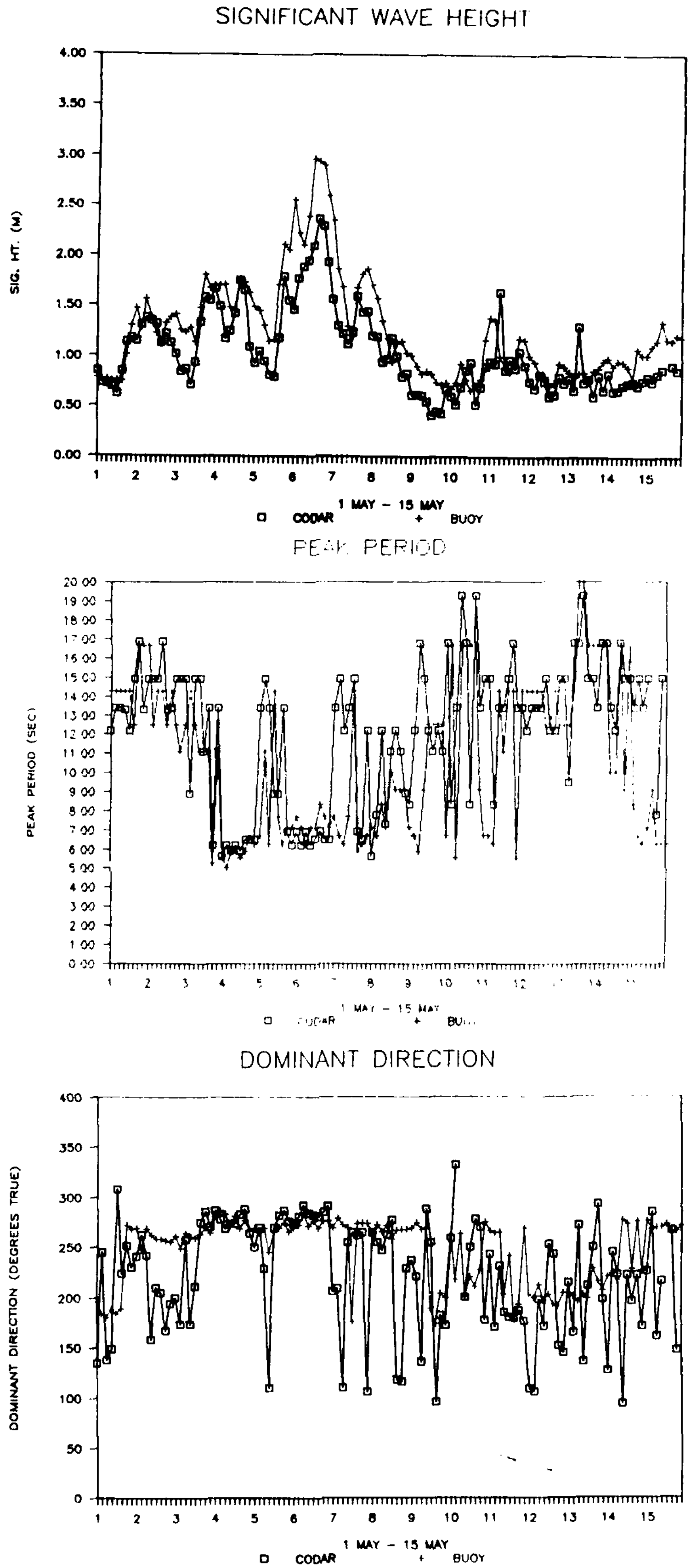


Figure A1. Phase I time series plots for 1-15 May 1986

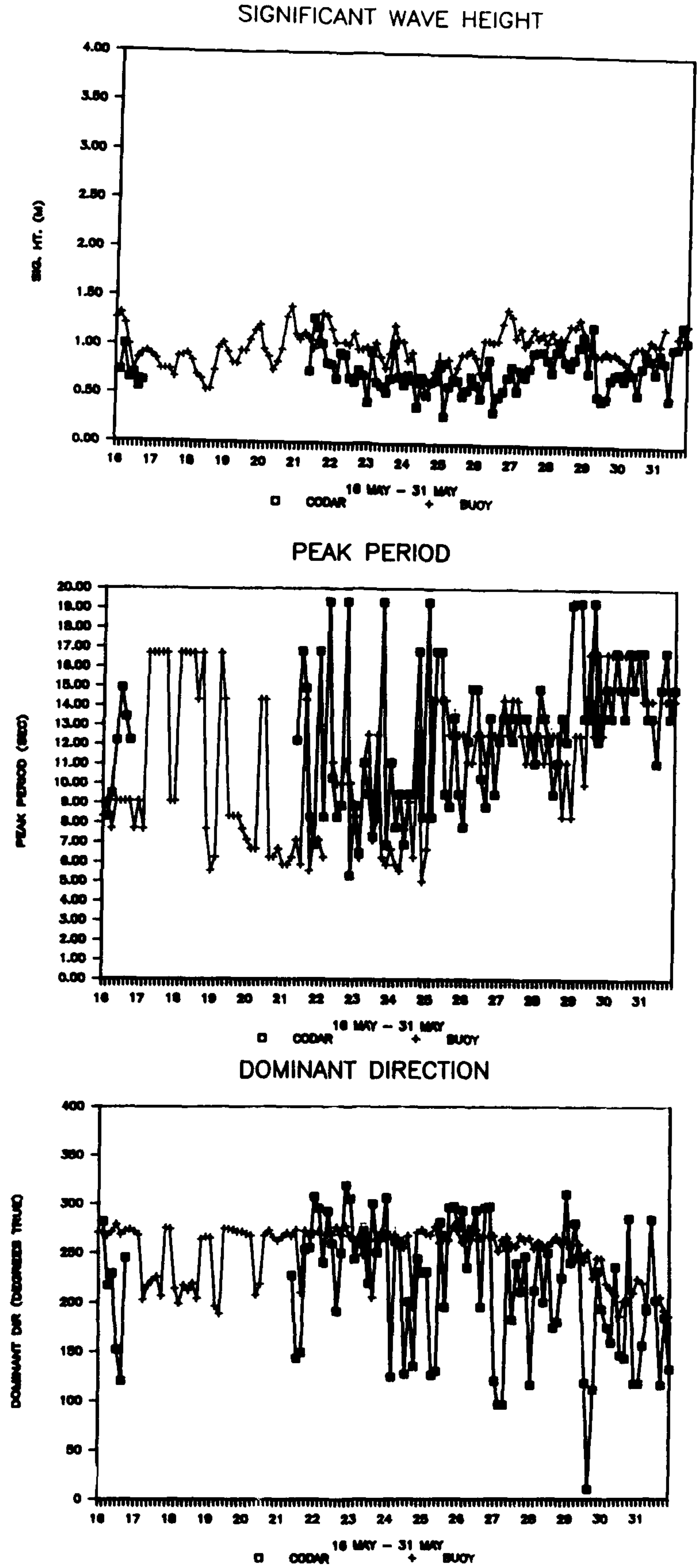
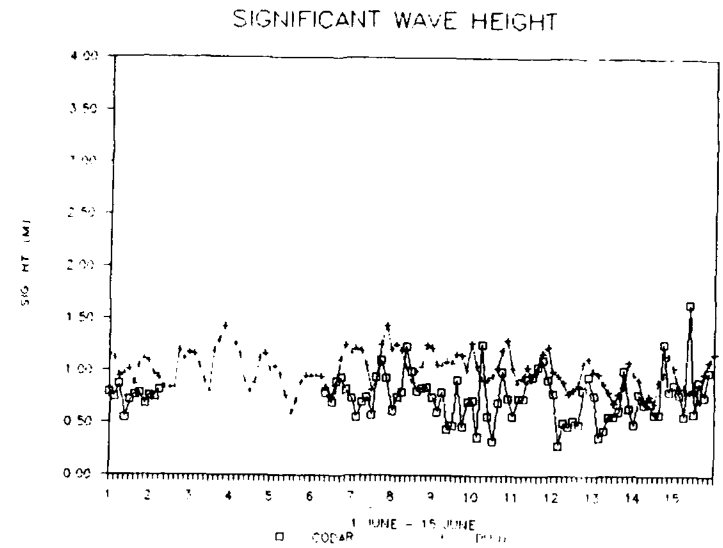
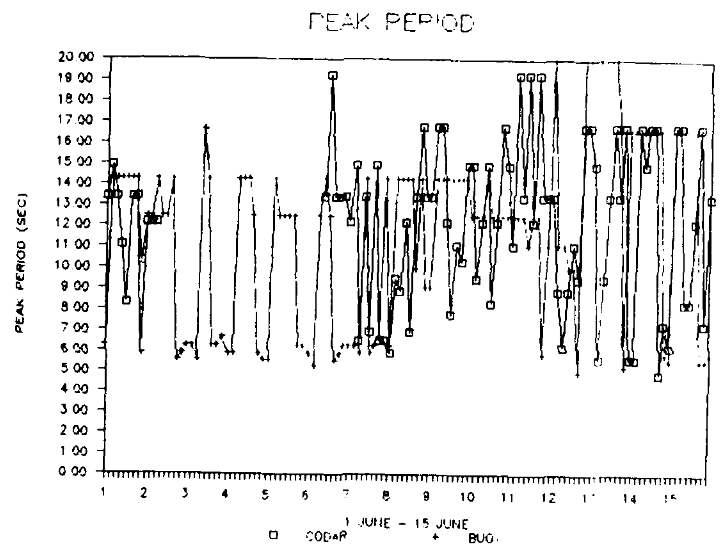


Figure A2. Phase I time series plots for 16-31 May 1986





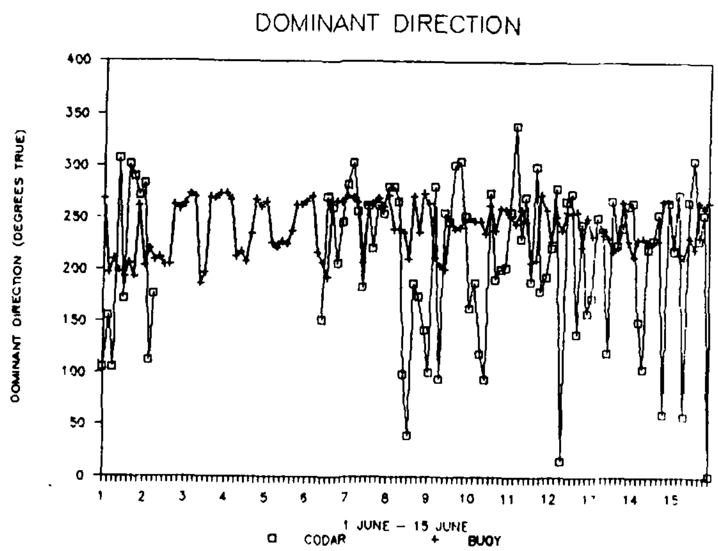


Figure A3. Phase I time series plots for 1-15 June 1986

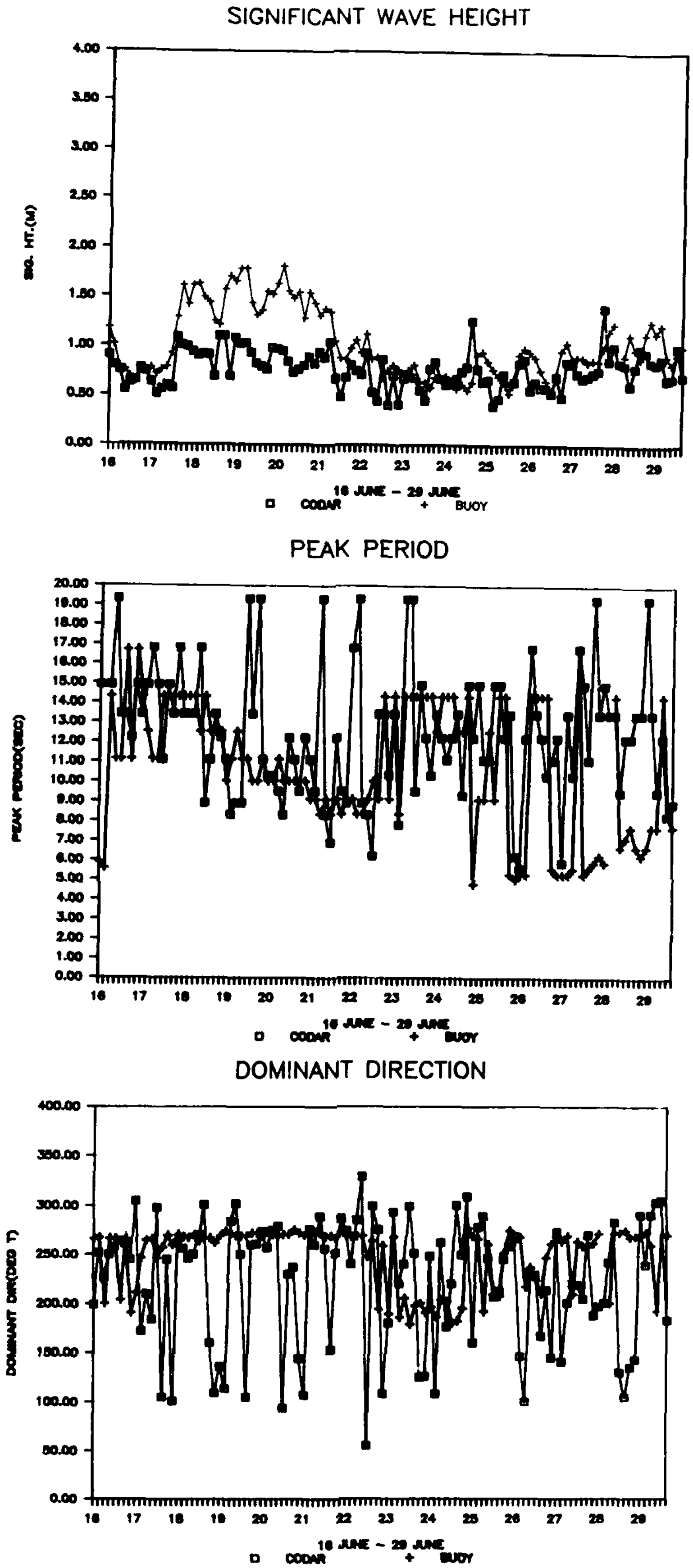


Figure A4. Phase I time series plots for 16-29 June 1986

APPENDIX B: PHASE II TIME SERIES PLOTS

1. Time series of significant wave height, peak spectral period, and dominant wave direction, as measured by CODAR, the NOAA buoy, and Waveriders #630, #650, and #660, are plotted in weekly intervals from 15 September 1987 to 9 February 1988. Arrows indicate wind speed and direction at the NOAA buoy.

2. Waverider #630 was located approximately 4 miles (6 km) offshore and was therefore shoreward of the CODAR coverage area. It is included in the time series plots but was left out of all data analysis procedures.

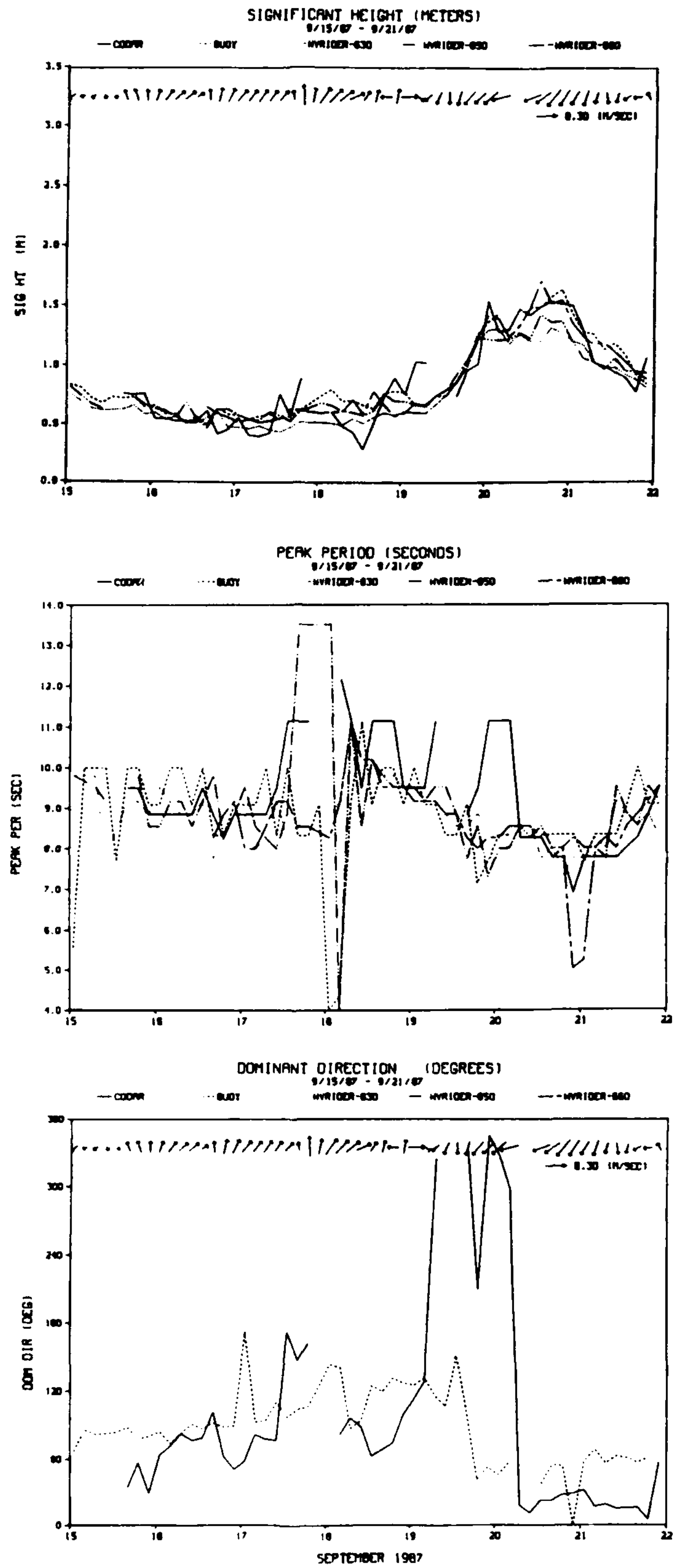


Figure B1. Phase II time series plots for 15-21 September 1987

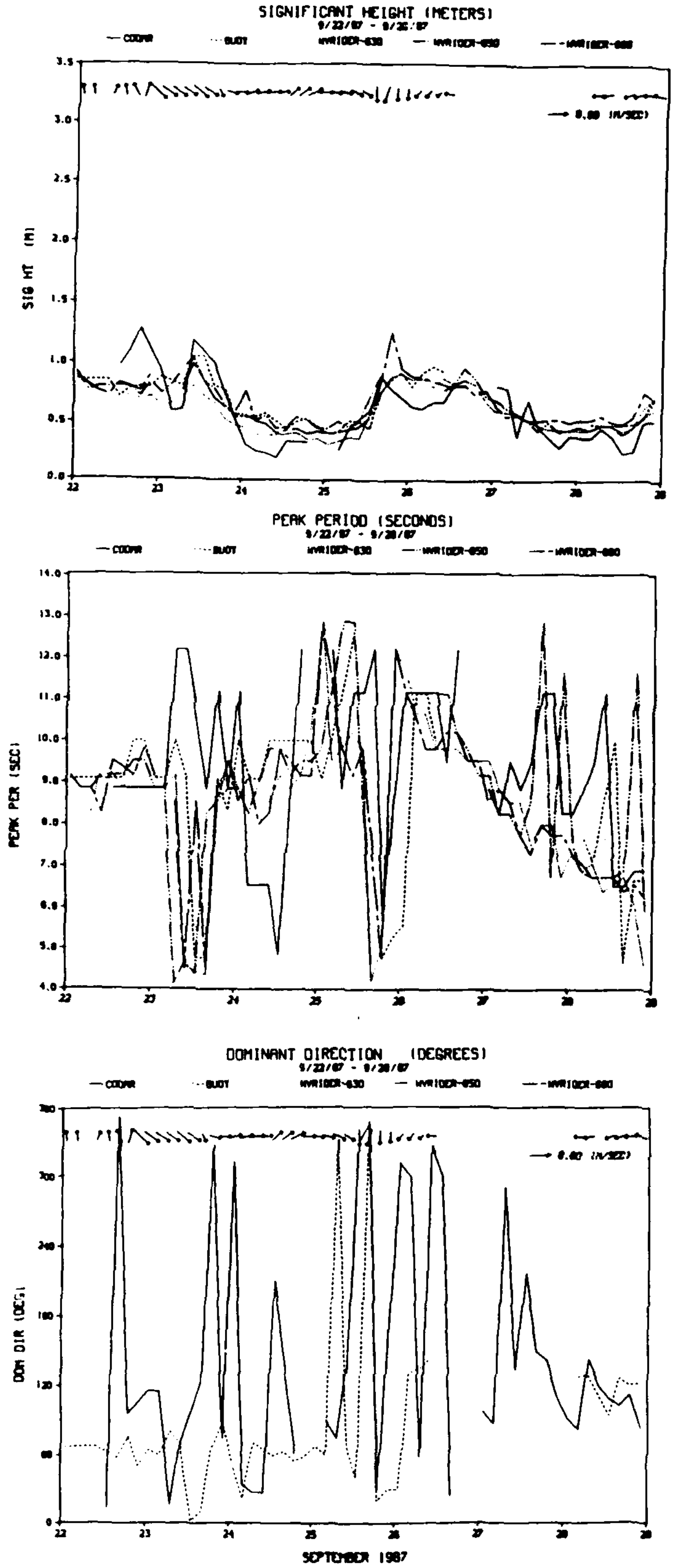


Figure B2. Phase II time series plots for 22-28 September 1987

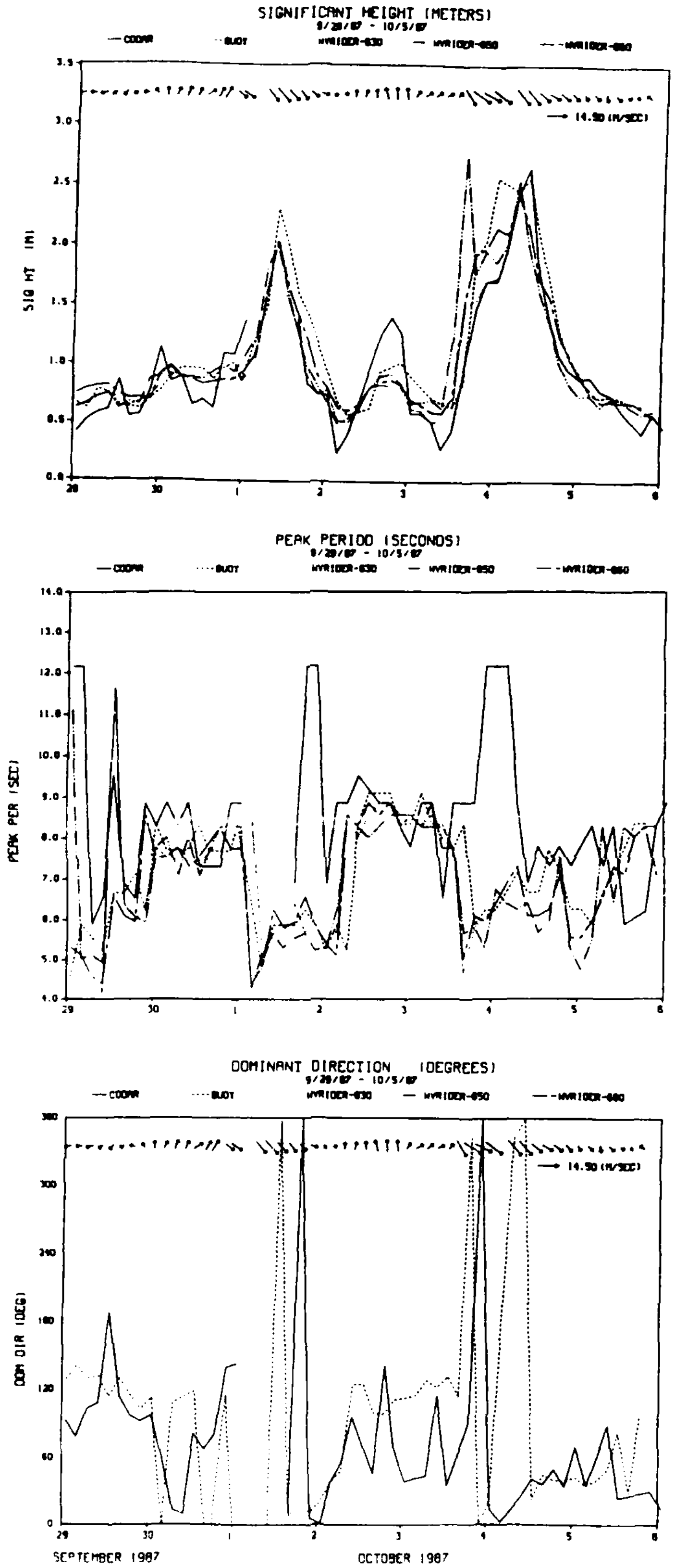


Figure B3. Phase II time series plots for 29 September - 5 October 1987

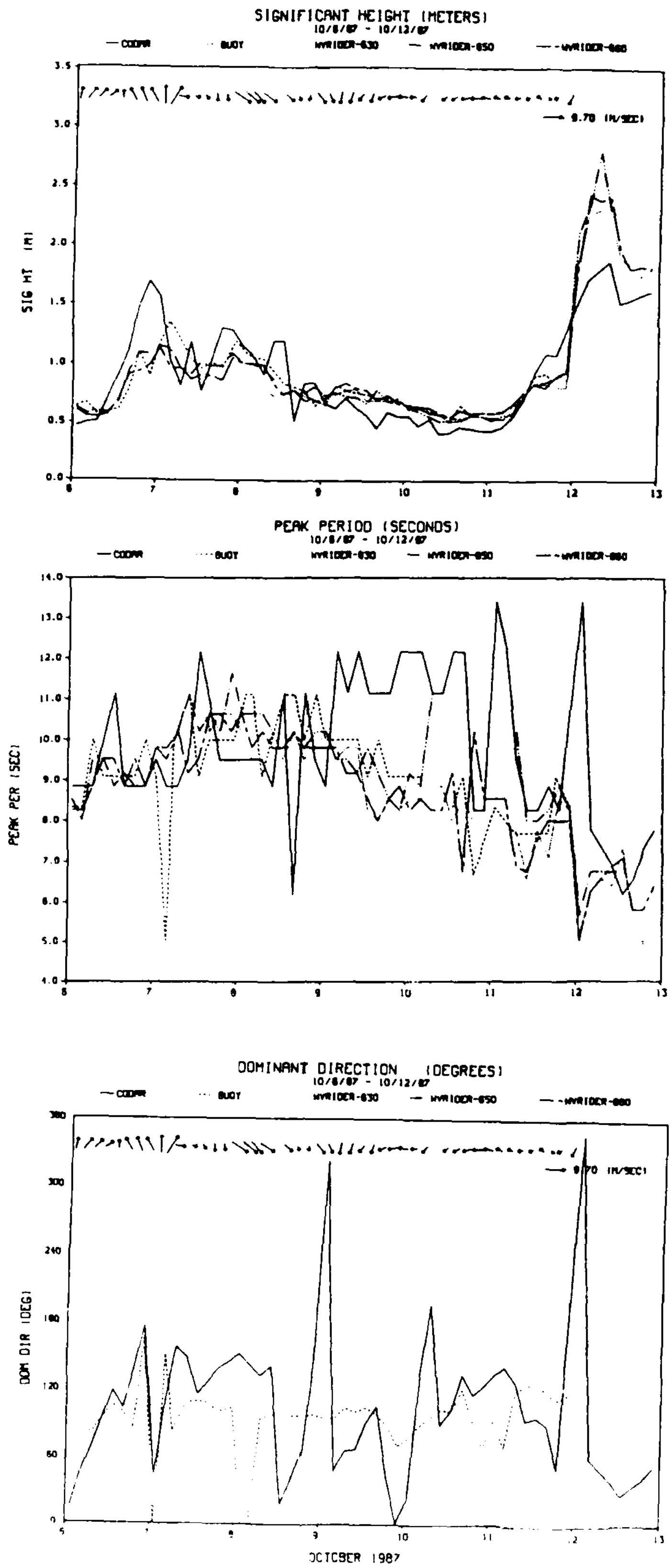


Figure B4. Phase II time series plots for 6-12 October 1987

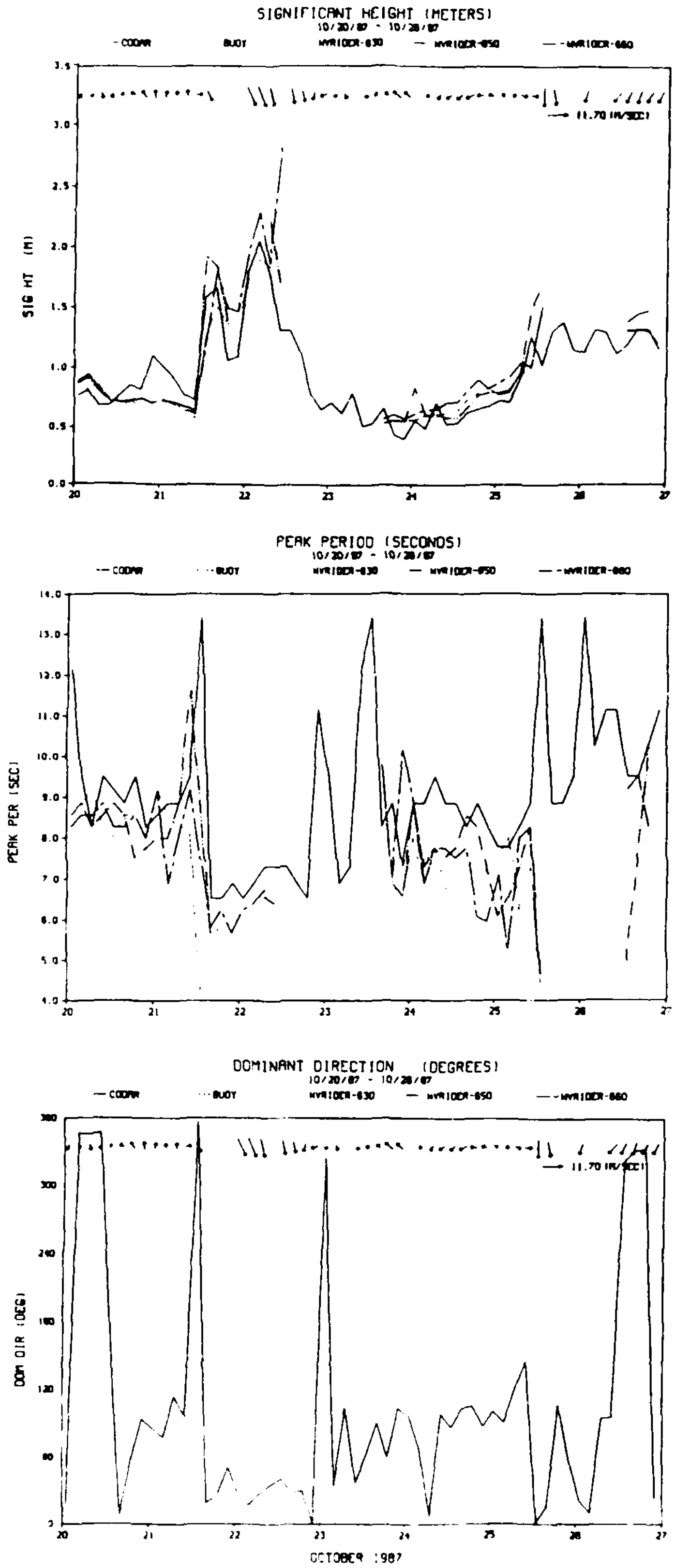


Figure B5. Phase II time series plots for 20-26 October 1987

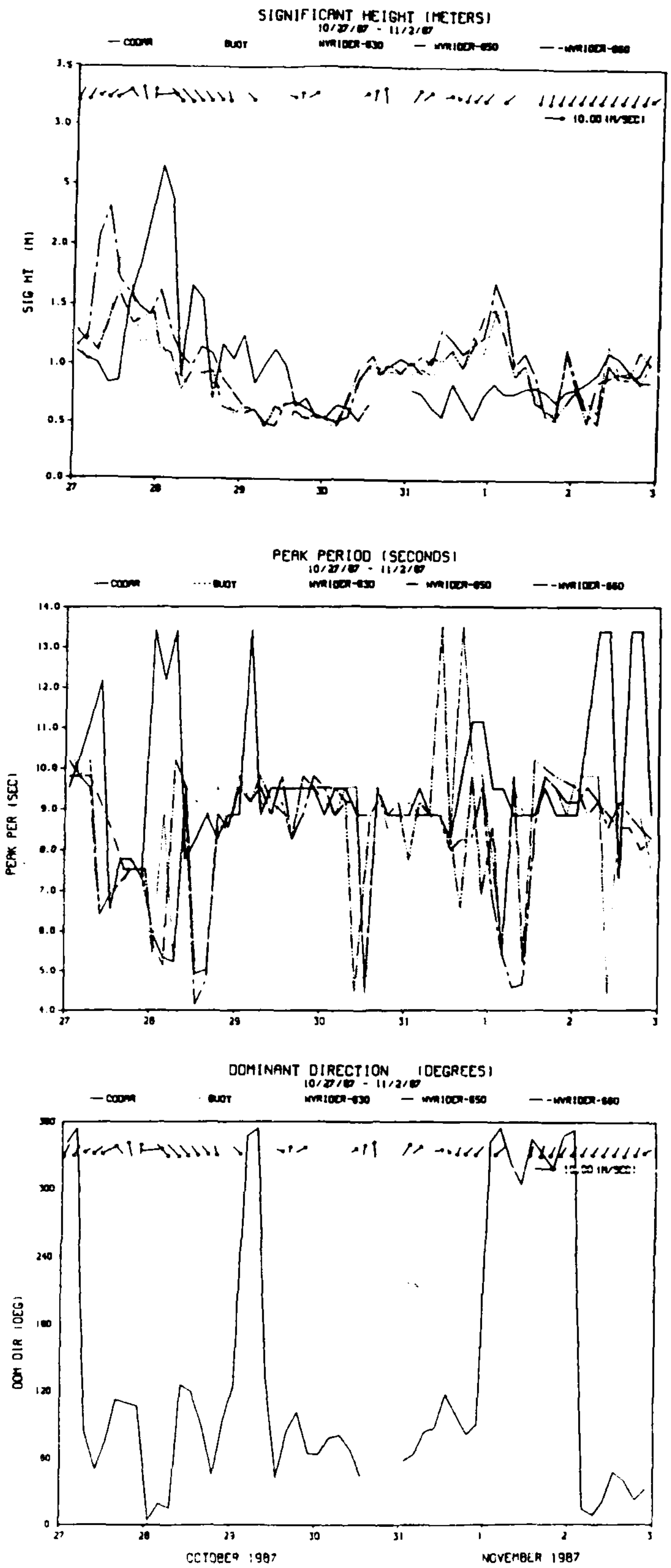


Figure B6. Phase II time series plots for 27 October - 2 November 1987

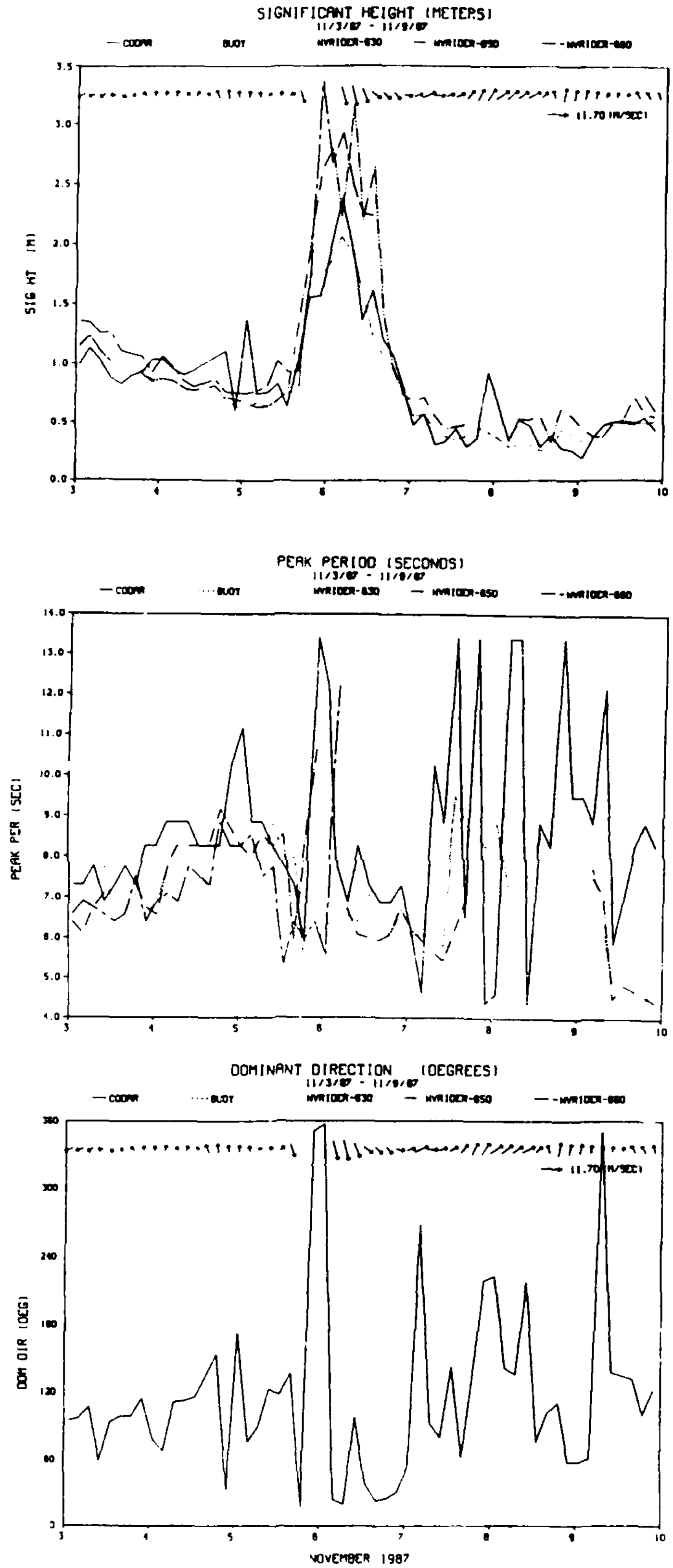


Figure B7. Phase II time series plots for 3-9 November 1987

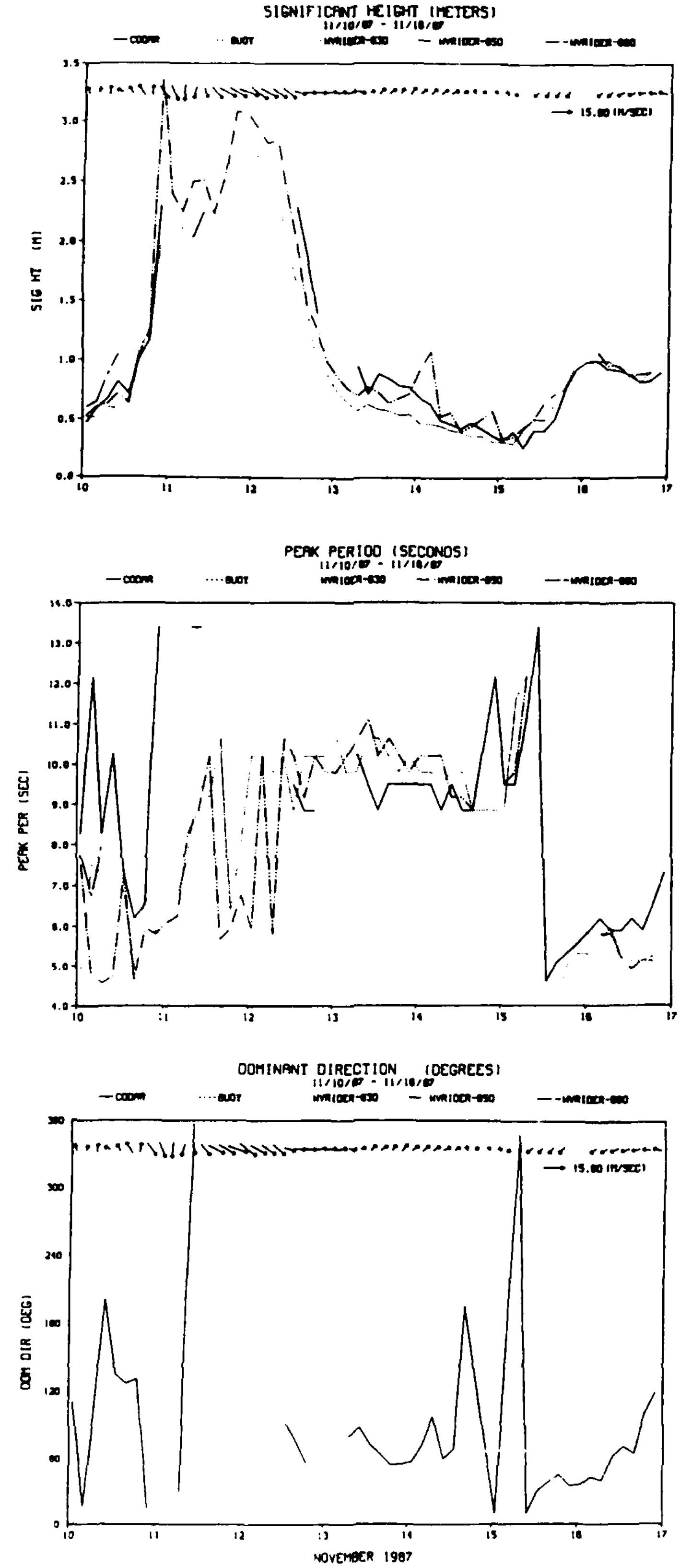


Figure B8. Phase II time series plots for 10-16 November 1987

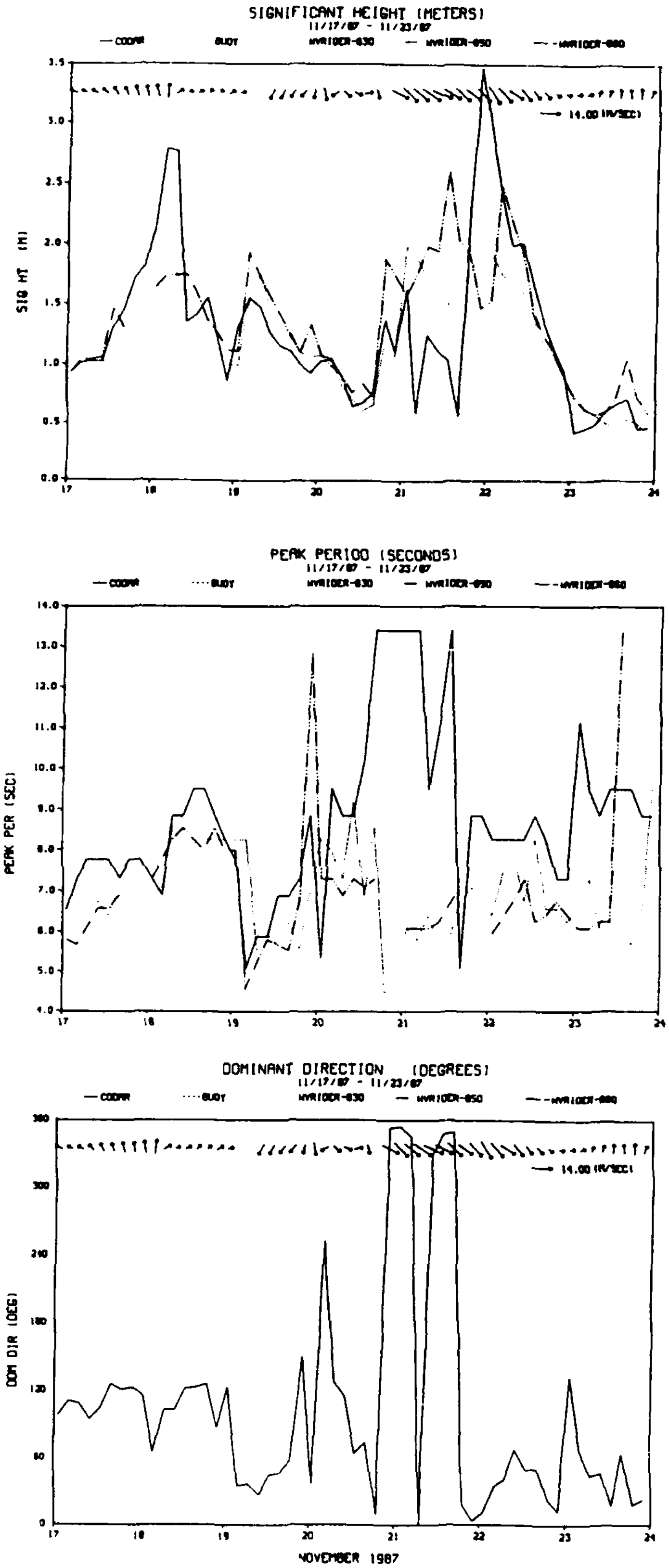


Figure B9. Phase II time series plots for 17-23 November 1987

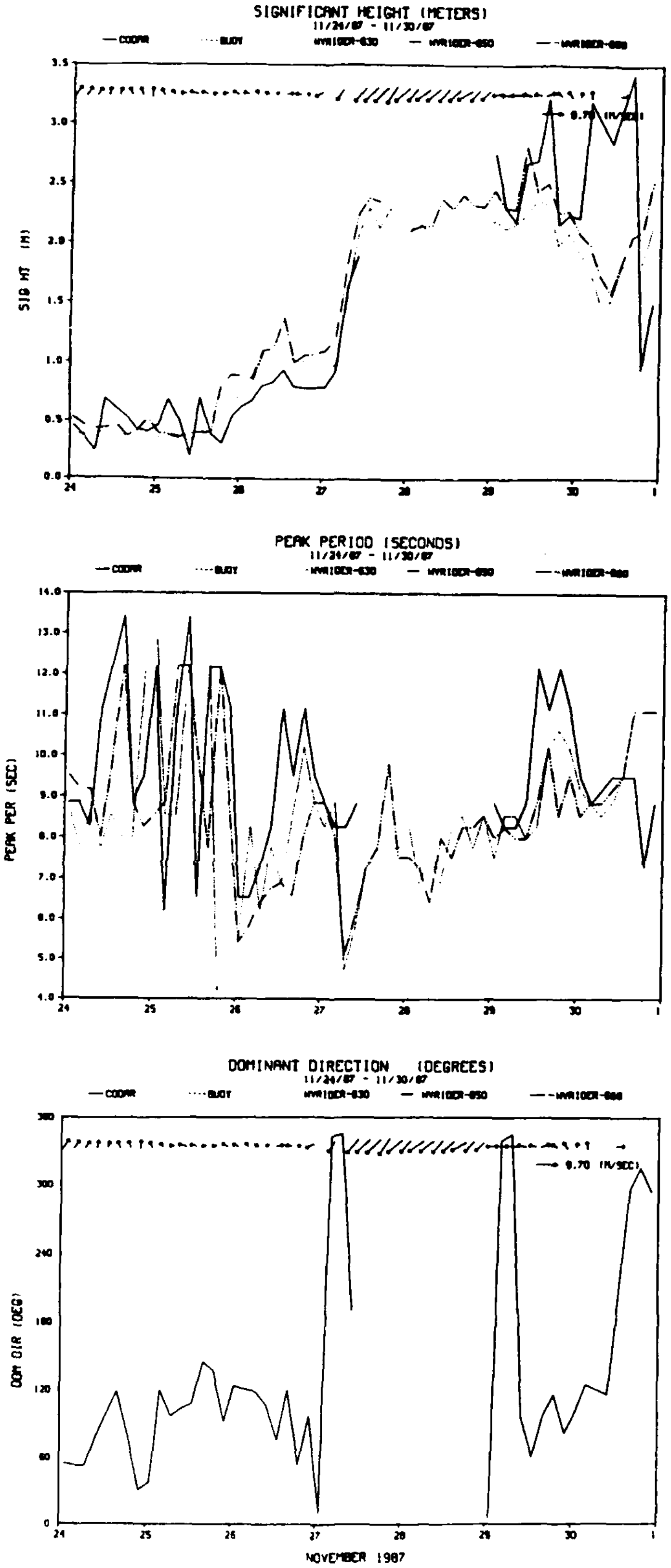


Figure B10. Phase II time series plots for 24-30 November 1987

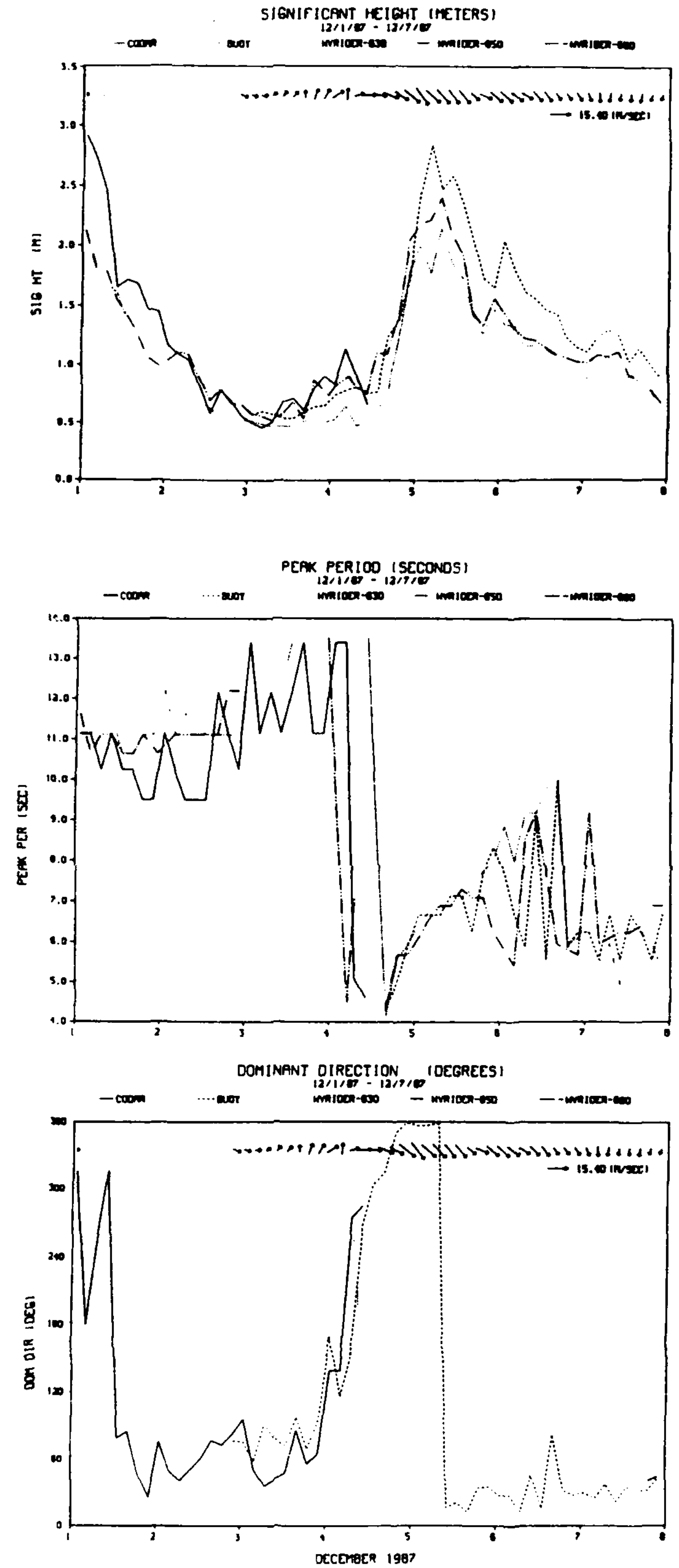


Figure B11. Phase II time series plots for 1-7 December 1987

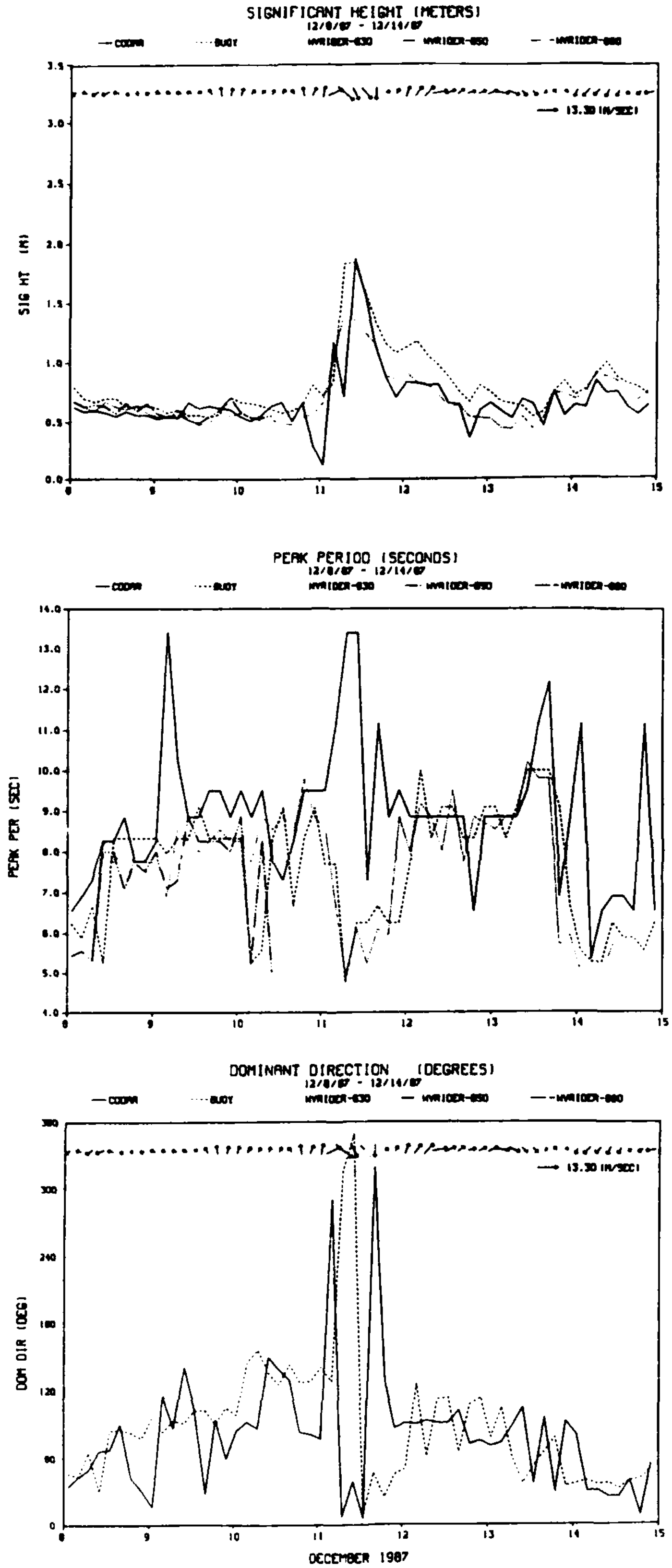


Figure B12. Phase II time series plots for 8-14 December 1987

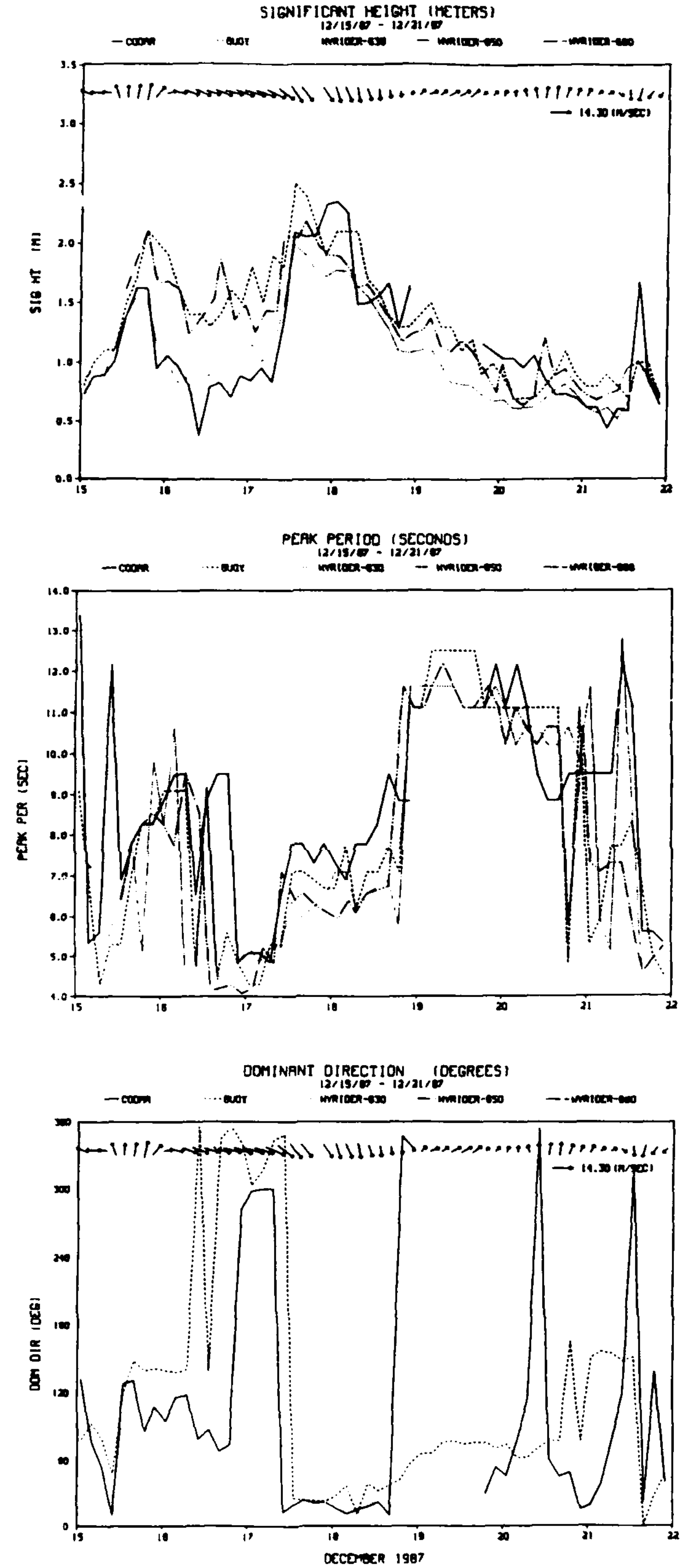


Figure B13. Phase II time series plots for 15-21 December 1987

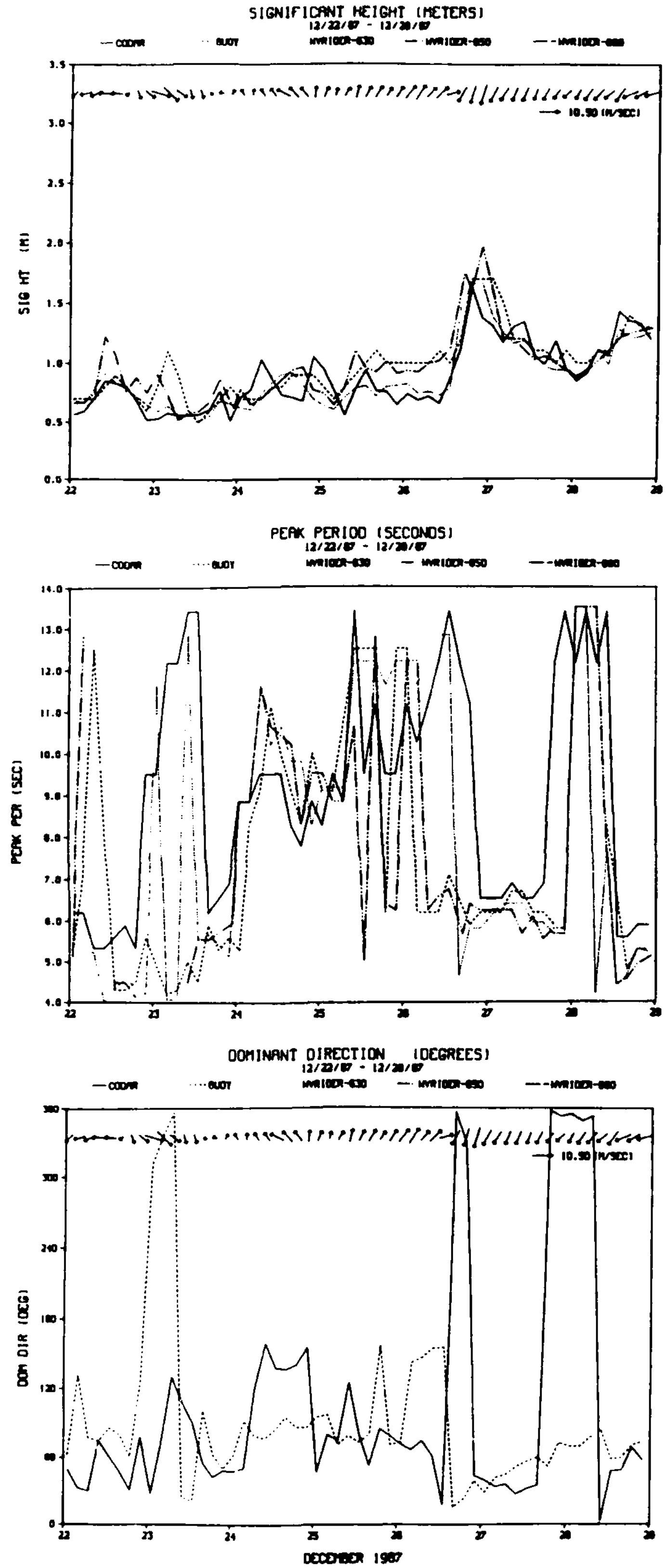


Figure B14. Phase II time series plots for 22-28 December 1987

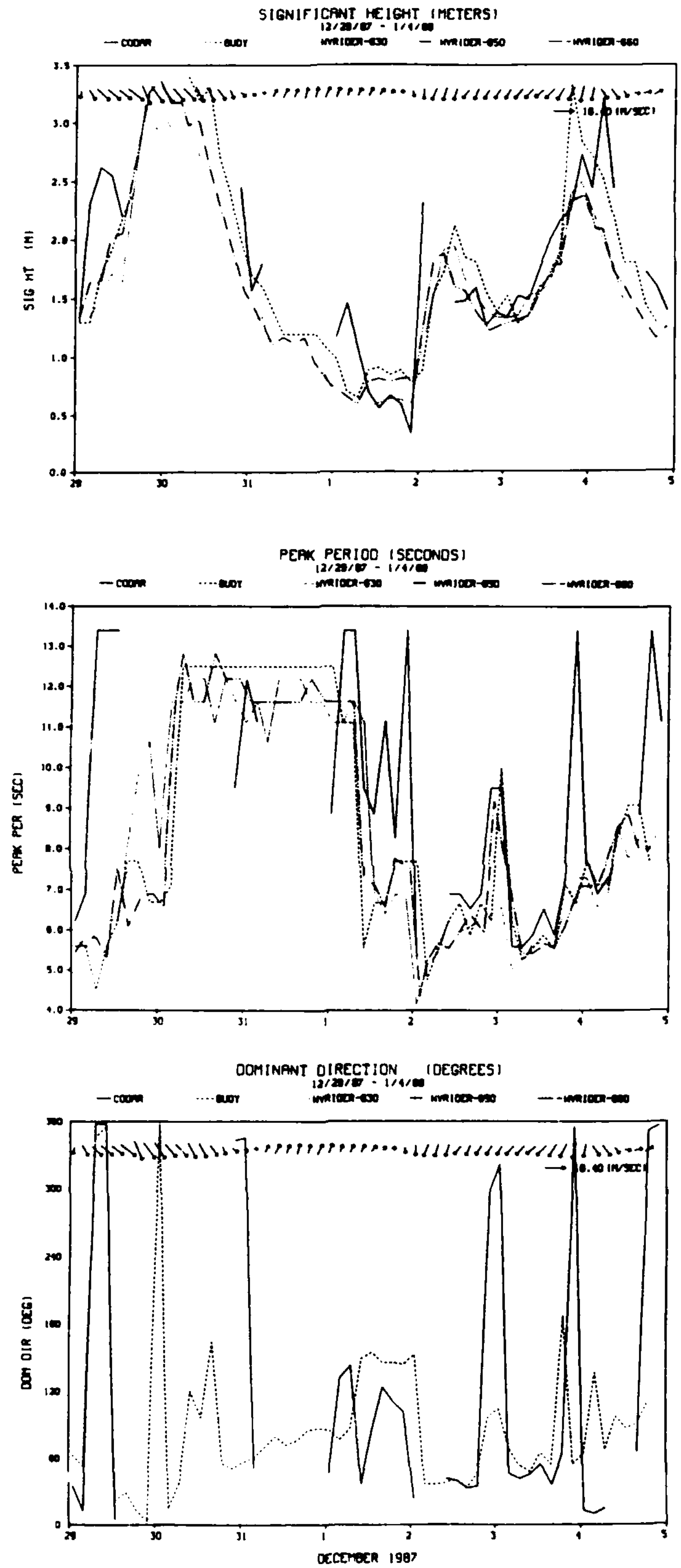


Figure B15. Phase II time series plots for 29 December - 4 January 1988

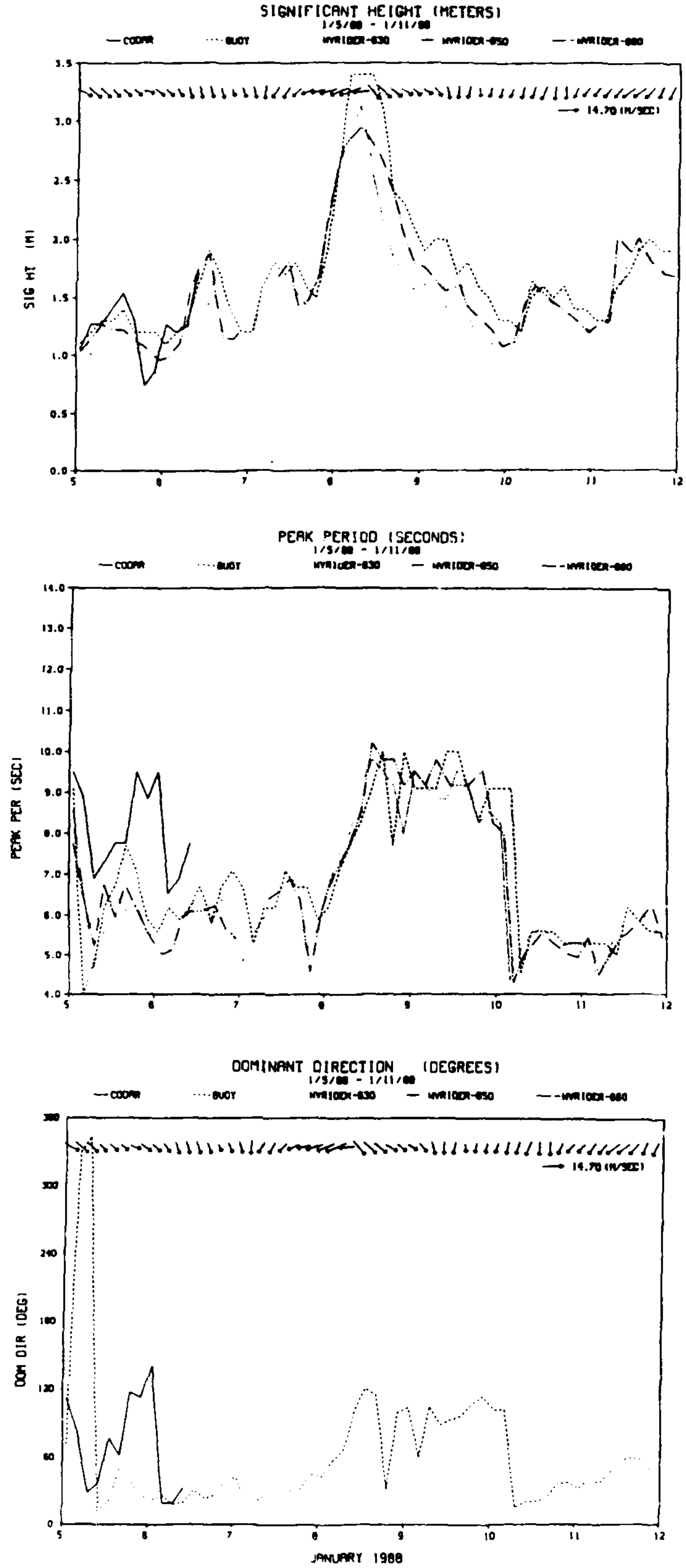


Figure B16. Phase II time series plots for 5-11 January 1988

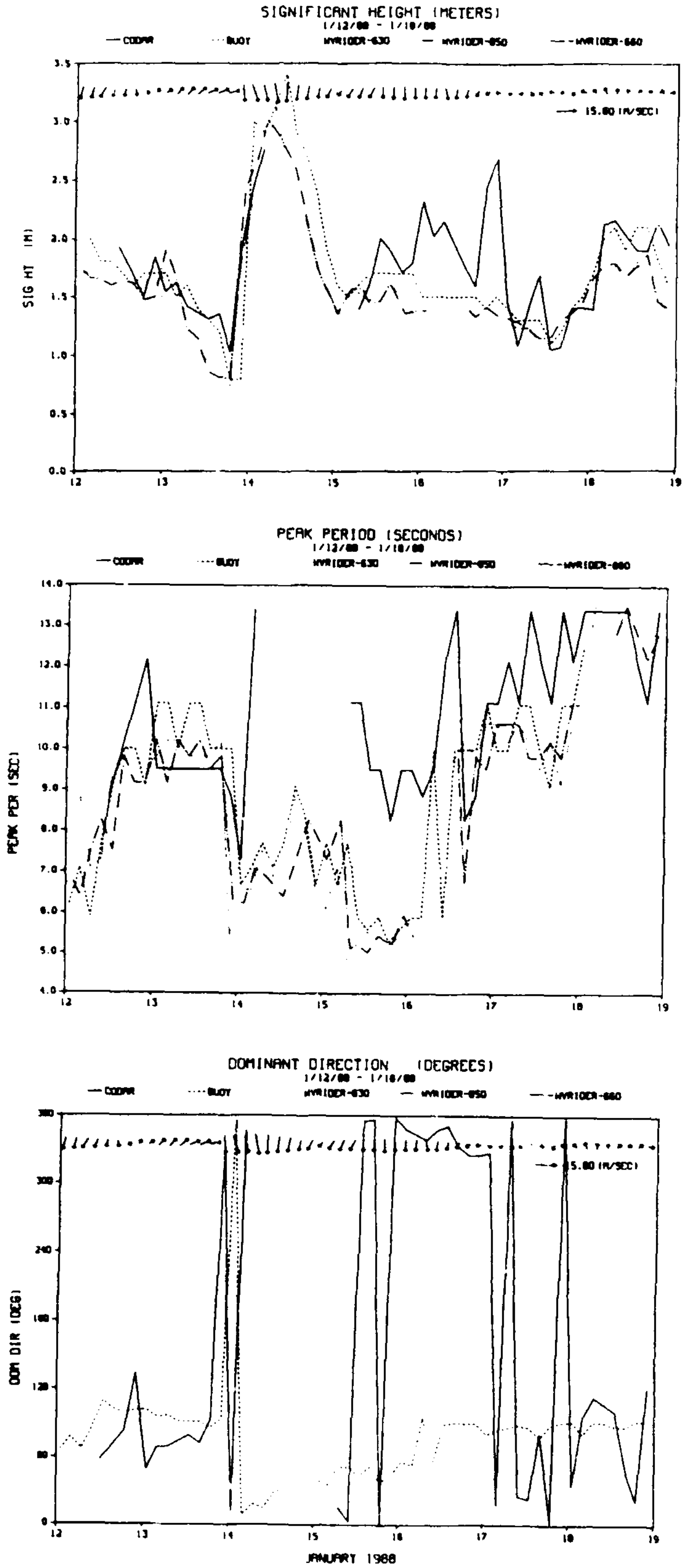


Figure B17. Phase II time series plots for 12-18 January 1988

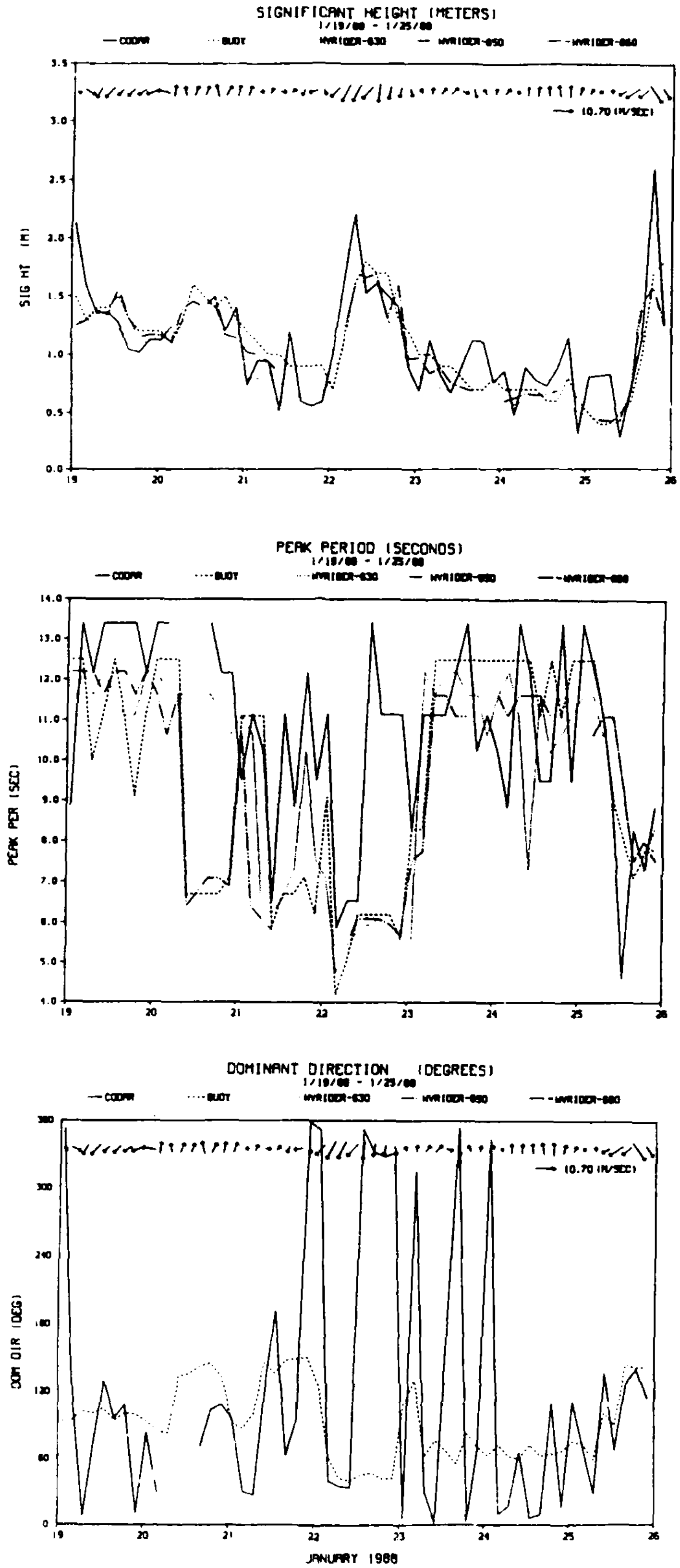


Figure B18. Phase II time series plots for 19-25 January 1988

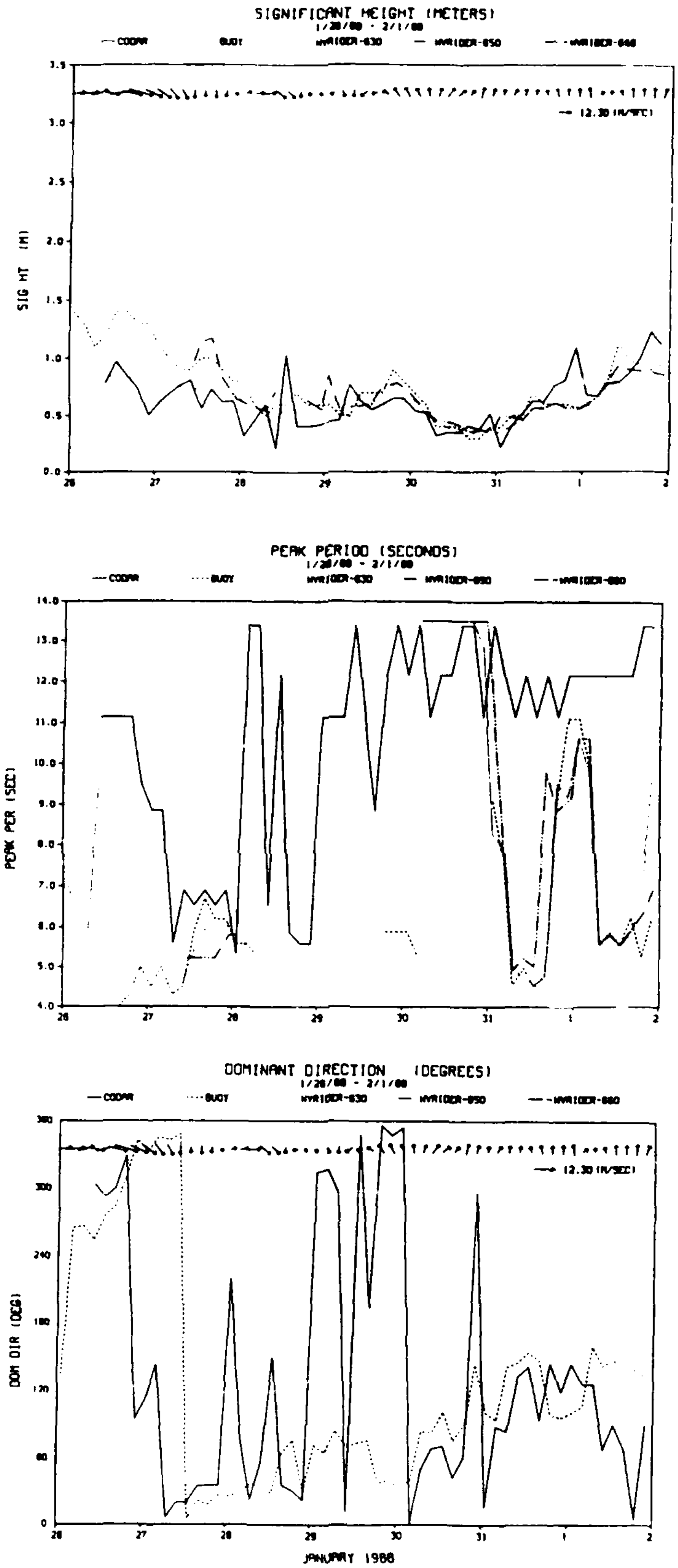


Figure B19. Phase II time series plots for 26 January - 1 February 1988

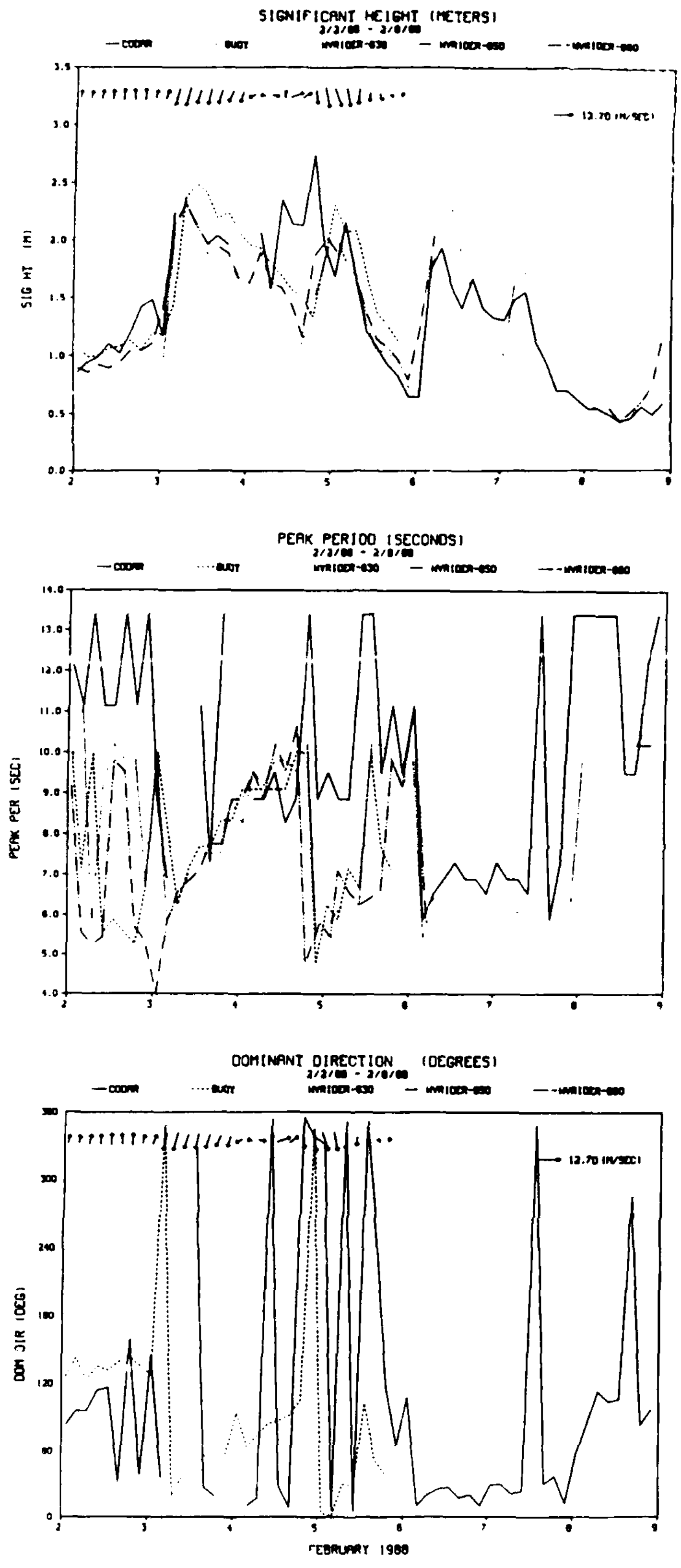


Figure B20. Phase II time series plots for 2-8 February

APPENDIX C: WAVE REFRACTION ANALYSIS

PART I: INTRODUCTION

1. A simple method to "unrefract" waves from nearshore depths to offshore depths or refract waves from offshore to nearshore depths was developed using results from the FORTRAN program TWAVE2. TWAVE2 uses Snell's law to refract and shoal discrete components of a directional wave energy spectrum over straight, parallel bottom contours. Calculated spectra are limited by the JONSWAP spectrum in deep water and by the TMA depth-limited spectrum in shallow water. A detailed description of TWAVE2 is given in Coastal Engineering Technical Note (CETN)-I-33.*

2. The graphical refraction method presented in the Shore Protection Manual (SPM 1984) (Plate C-6, Page C-35) uses Snell's law to refract monochromatic waves over straight, parallel bottom contours. This method is convenient since the wave parameters are related in graphic form and data can easily be extracted. In comparing the results from TWAVE2 and the SPM method, it was found that the refracted wave angles were consistently close and thus helped confirm the use of TWAVE2 results prior to final data analysis for this study.

3. The procedures for developing this refraction/"unrefraction" method are presented in this appendix, including a description of the resulting scatter plot.

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* References cited in the appendixes can be found in the References at the end of the main text.

PART II. DATA COLLECTION

4. The two wave gage systems involved in this study were located at the Field Research Facility (FRF). A linear array, consisting of 10 pressure gages, was placed shore-parallel at a nearshore depth of approximately 30 ft (9 m). Data were collected at 3-hr increments from 0100 15 September 1987 to 0400 9 October 1987. Also during this period, CODAR data were collected offshore in a depth of approximately 90 ft. Wave direction was taken in degrees as positive, counter-clockwise with incoming shore-parallel wave crests at zero degree.

5. The linear array data consisted of 192 files of directional spectral information, one file for each 3-hr increment of data collection. Eighteen spectral peak periods ranging between 3.25 and 13.56 sec were identified from the 192 files.

6. TWAVE2 was run to refract waves for the 18 spectral peak periods. The initial wave approach angles were in 10-deg increments from 0 to 90 deg. Each period required one TWAVE2 run for each initial wave approach angle. An initial depth of 1,000 ft (305 m) and an energy-based significant wave height H_{mo} of 10 ft (3 m) were chosen for each run. TWAVE2 refracted the waves from 1,000 to 100 ft (305 to 3 m) and continued the refraction in 10-ft (3 m) increments from 100 to 10 ft (30 to 3 m).

7. Output files from a TWAVE2 run at a specified spectral peak period and specified initial wave approach angle consisted of a summary of wave heights, nondirectional spectra, and directional spectra for depths from 100 to 10 ft (30 to 3 m) in 10-ft (3 m) increments. For the purpose of this study, only directional spectral data were necessary.

8. It was found that wave refraction increased with increasing peak period and decreasing incident wave approach angle. These results are consistent with Snell's Law.

PART III. DATA SUMMARY

9. The refracted wave angles at 90 (27 m) and 30 ft (9 m) were extracted from each TWAVE2 directional spectra data output file. Eighteen data files which correspond to the 18 linear array spectral peak periods were created. Each file contained the refracted wave angles at 90 (27) (variable Y) and 30 ft (9 m) (variable X) for each incident wave approach angle and spectral peak period. Each data file was then represented on a scatter plot, as shown in Figure C1.

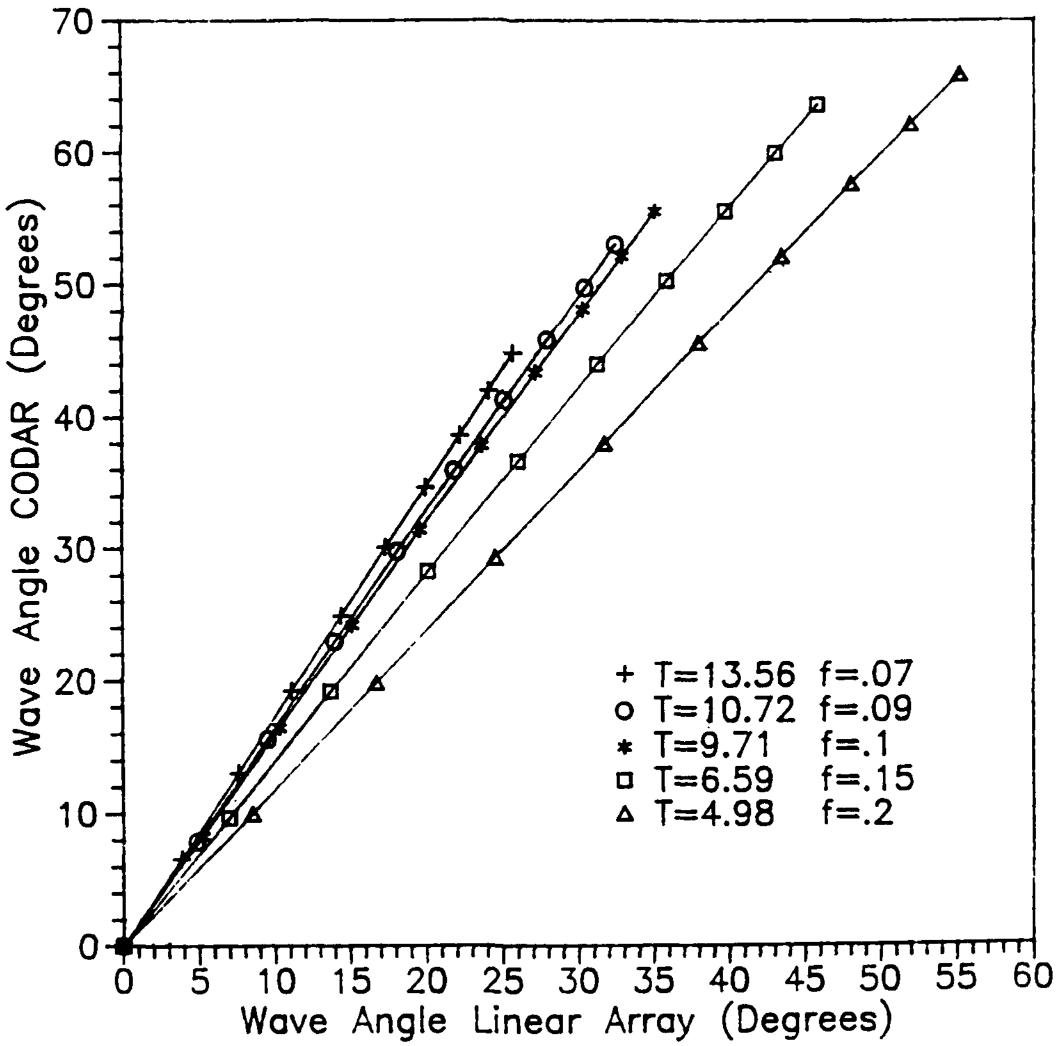

Figure C1. Scatter plot of refracted wave angles

10. For clarity, only 7 of the 18 spectral peak periods are represented, and each line represents a specific period. The ordinate represents refracted waves angles (in degrees) at 90 ft (27 m) (CODAR depth) and the abscissa represents refracted wave angles (in degrees) at 30 ft (9 m) (linear array depth). Each point represents a pair of 90- (27-) versus 30-ft (9 m) (Y, X) refracted wave angles for a given initial wave approach angle from 0 to 90 deg. The method of least squares was used to determine linear regression coefficients. The standard error and correlation coefficient were also calculated. The 18 spectral peak periods with corresponding regression coefficients, standard error, and correlation coefficient are presented in Table C1.

11. Figure C1 can be used to refract a wave from a 90- (27) to a 30-ft (9 m) depth, or "unrefract" a wave from a 30- (9) to a 90-ft (27 m) depth. The procedure to "unrefract" a wave from a 30-ft (9 m) depth to a 90-ft (27 m) depth using Figure 1 is as follows:

- a. Choose the initial wave angle along the x-axis to "unrefract" from.
- b. Find the regression line which corresponds to the spectral peak period of interest.
- c. Draw a line perpendicular to the x-axis from the initial wave angle to the chosen regression line.
- d. The "unrefracted" wave angle at 90 ft (27 m) is the value along the y-axis which corresponds to the point of intersection of the perpendicular line and the regression line.

12. To refract a wave for the same conditions, follow the above procedure, but choose an initial wave angle along the y-axis and work toward the x-axis.

Table C1
Data Summary

Spectral Peak Period	Y = a + bX			
	a	b	Standard Error, deg	Correlation Coefficient
3.25	-0.084	1.079	0.1	1.00
3.59	-0.084	1.079	0.1	1.00
4.35	-0.074	1.108	0.1	1.00
4.54	-0.072	1.133	0.1	1.00
4.98	-0.091	1.199	0.1	1.00
5.24	-0.068	1.237	0.1	1.00
5.52	0.015	1.276	0.2	1.00
5.83	0.012	1.316	0.2	1.00
6.19	0.132	1.354	0.2	1.00
6.59	0.129	1.393	0.2	1.00
7.04	0.182	1.428	0.3	1.00
7.56	0.214	1.462	0.3	1.00
8.16	0.763	1.481	0.5	1.00
8.87	0.192	1.539	0.2	1.00
9.71	0.135	1.585	0.1	1.00
10.72	0.084	1.621	0.1	1.00
11.10	0.061	1.637	0.1	1.00
11.98	-0.026	1.698	0.0	1.00
13.56	-0.087	1.744	0.1	1.00